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Evaluation of Asphalt Cements for Low Temperature Performance

by

©

LEUNG, SUI CHUNG

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OF Master of Science

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....

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....

....

Date October 10, 1986

To

My Wife and My Son Eric

Abstract

The primary objective of this research is to evaluate the low temperature performance of asphalt cements produced from different crude sources of western Canada.

The research comprises the collection and analysis of routine asphalt cement test data obtained from Alberta Transportation, and the laboratory testing of selected asphalt cement samples from different crude sources.

From the routine test data, the properties of asphalt cements produced from various refineries in terms of penetration, viscosity, temperature susceptibility and resistance to aging are evaluated. It is noted that in general, most of the asphalts used in road construction have met the requirements of the Alberta Transportation specification. Within the limit of the specification, however, variation of properties and temperature susceptibility among asphalts of the same grade but produced by different refineries exists. It is also noted that the properties of asphalt, particularly with respect to low temperature performance, have improved since the revision of asphalt specification in 1980.

Selected asphalt samples of different crude sources were obtained from different suppliers and tested. Two types of laboratory tests were carried out. Conventional physical tests were carried out to define the rheological properties and temperature susceptibility parameters which were utilized in evaluating the low temperature performance of these asphalts.

The tensile splitting test, which has been used to test asphalt concrete cores at the University of Alberta and improved in this project, was utilized in testing asphalt mixes prepared from the different asphalt cements. The asphaltic concrete cylinders were tested at four different temperatures, 0 °C, -10 °C, -20 °C and -30 °C. Again, the tensile properties obtained from the tests were utilized in evaluating the asphalt cements for low temperature performance.

From the laboratory test results, it is noted that asphalts produced from different crude sources have different temperature susceptibilities and consequently, different low temperature performance. This is illustrated by the failure strain and stiffness obtained from the tensile splitting test as well as the indirect estimation of asphalt stiffness by various methods. It is also confirmed that softer grade asphalt does not necessarily possess better resistance to low temperature cracking because temperature susceptibility is also an important factor in evaluating asphalt performance at low temperatures.

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1. INTRODUCTION

1.1 General

The behaviour of asphalt concrete pavement at low temperatures, particularly with regard to transverse cracking, has been of particular concern to many highway engineers and researchers in Canada, United States and other countries since the 1960's. It is well known that low temperature transverse cracking, which is a sign of pavement failure, occurs when the thermal stress induced by cooling, exceeds the tensile breaking strength of the pavement (1). A variety of factors, for example, climatic effects, subgrade type, asphalt properties, mix properties and mix design, pavement design, pavement age and traffic effects, has been reported to influence the occurrence and severity of transverse cracking. Among these factors, asphalt properties have received the most attention from investigators and have been proved to have a significant effect on transverse cracking (2).

The properties of asphalt cement, for example, penetration, viscosity, ductility, stiffness and temperature susceptibility, etc., vary depending on the source of crude oil from which the asphalt cement is refined. This is indicated by differences in low temperature field behaviour of asphaltic concrete composed of similar asphalts but obtained from different suppliers, as reported in several Canadian road test projects (3,4,5). Particularly, "high viscosity" asphalt cements (i.e. low temperature susceptibility) which were produced from heavy crude sources in Western Canada, have been reported to perform better than the "low viscosity" (i.e. high temperature susceptibility) asphalt cements manufactured from lighter crude oils.

In order to reveal the performance of the asphalt cements produced from heavy crude sources in Western Canada, an evaluation of the properties of the asphalt cements, particularly with regard to temperature susceptibility and low temperature fracture characteristics, is warranted. If the superior characteristics of these asphalt cements are confirmed, significant impact on performance and costs of asphalt pavements will be anticipated.

1.2 Objectives of the Thesis

The objectives of this thesis are as follows:

1. To determine the rheological properties and temperature susceptibility of asphalt cements that have been used recently in road construction in Alberta,
2. To review the development of the current specification for asphalt cement adopted by Alberta Transportation, and to evaluate the effect of the historical change of the specifications to the rheological properties and temperature susceptibilities of the Alberta asphalt cements.
3. To evaluate the low temperature performance of asphalt cements produced from heavy crude sources in Western

Canada. Temperature susceptibility and low temperature fracture characteristics are considered to be the major properties of asphalt cement that are relevant to low temperature performance of asphalt concrete pavement.

4. To develop and update the tensile splitting test as a method to evaluate the low temperature tensile properties of asphalt concrete mixtures.

1.3 Research Approach

The research program was divided into two parts, namely, collection and analysis of Alberta Transportation asphalt cement test data, and laboratory testing of selected asphalt cement samples.

1.3.1 Collection and Analysis of Alberta Transportation Test Data

Conventional routine asphalt cement test data were obtained from the province's main asphalt cement user, Alberta Transportation. Two sets of data were obtained, one from the year of 1979 and one from the year of 1984 representing test data prior to and after the 1980 change of asphalt specification.

The properties of asphalt cements produced from various refineries in terms of penetration, viscosity, temperature susceptibility and resistance to Thin Film Oven Test aging were evaluated.

The development of the present Alberta Transportation specification for asphalt cement was reviewed and its effects on the historical change of the properties of asphalt cement are discussed.

1.3.2 Laboratory Testing Program on Selected Asphalt Samples

Asphalt cement samples of 85/100 and 200/300 grades from different crude sources were obtained from different suppliers to represent asphalts of low and high temperature susceptibility, and asphalts of hard and soft grade.

Two types of testing were carried out:

1. Conventional physical tests - asphalt cement samples were tested to define rheological properties and temperature susceptibilty parameters which were utilized in evaluating the low temperature performance of these asphalts.
2. Tensile splitting test - Asphalt concrete specimens were prepared and tested to determine the low temperature tensile properties. Again, the tensile properties obtained were utilized in evaluating the low temperature performance of these asphalt concrete mixtures.
   The tensile splitting test method was improved with a new data acquisition and processing system.

1.4 Organization of the thesis

Chapter 2 contains a review of methods and parameters that have been used in evaluating the low temperature performance (tranverse cracking) of asphalt cement. Particularly, temperature susceptibility and fracture characteristics of asphalt cement are discussed in detail.

Chapter 3 presents the characteristics of asphalt cement commonly used in Alberta. It also discusses the range and extent of variability of the asphalt cement properties with respect to refineries.

Chapter 4 first presents the common grading systems for asphalt cement in North America and the historical change of asphalt specifications in Alberta. The chapter then discusses the effects of the 1980 change of specification to the rheological properties and temperature susceptibility.

Chapter 5 contains a brief outline of the laboratory testing program and the results of conventional physical tests on selected asphalt cement samples from different crude sources. It then discusses the differences of properties and parameters of the samples with respect to crude sources and finally, the low temperature performances of these samples by means of the Bitumen Test Data Chart, Stiffness Modulus and Cracking Temperature.

Chapter 6 contains a brief description of the uses and development of the indirect tensile splitting test method. It also presents the results of the tensile splitting tests which are used to determine the low temperature tensile properties of asphalt concrete specimens prepared with selected asphalt cements as characterized in chapter 5.

Chapter 7 contains the conclusions of the thesis and recommendations for further research to evaluate and characterize the properties of asphalt cement from heavy crude sources in Western Canada.

The appendices contain statistical summaries of as-supplied routine test data, detailed test results, details of the improved tensile splitting test method and listings of computer programs related to the tensile splitting test.

2. TEMPERATURE SUSCEPTIBILITY AND FRACTURE CHARACTERISTICS

2.1 Temperature Susceptibility of Asphalt

Temperature susceptibility is the rate at which the consistency of an asphalt cement changes with a change in temperature and is a very important property of asphalt cements. Figure 2.1 demonstrates schematically that two paving asphalts can have the same consistency at a particular temperature (for example, penetration at 25 C or viscosity at 60 C), but because of a difference in temperature susceptibility, they can have quite different consistencies when their temperatures are either raised or lowered.

Asphalt temperature susceptibility is highly dependent on the temperature range considered. It is well known that asphalt cement is a visco-elastic material which behaves as elastic solid at low temperature or short loading time, and as purely viscous fluid at high temperature or long loading time. At high temperature, asphalt behaves as a Newtonian substance. Its change in Newtonian viscosity (shear rate independent) with temperature is defined as the true temperature susceptibility. At lower temperatures, the response of asphalt to stress with temperature depends on the temperature range considered and is termed the 'pseudo' temperature susceptibility. Because asphalt cement rarely exhibits Newtonian behaviour in service temperature, this psuedo temperature susceptibility greatly influences pavement construction and performance (6).

Temperature susceptibility is directly related to the type of equipment used to determine asphalt consistency. One of the earliest methods of measuring temperature susceptibility was to measure penetration (ASTM D5) over a temperature range between 25 C and 0 C. The test is essentially a type of creep test and is a measure of the visco-elastic behaviour of asphalt. The penetration value obtained is not a true measure of viscosity.

Common viscosity tests for asphalt cement are usually ran at 135 C and 60 C and are rheologically much simpler than the penetration test. The kinematic viscosity at 135 C (ASTM D2170) measures purely viscous behaviour and for most asphalts, the absolute viscosity at 60 C (ASTM D2171) also measures viscous behaviour. However, for some hard, oxidized and waxy asphalts, the viscosity at 60 C is different at different levels of shear rate which indicates a non-Newtonian, visco-elastic behaviour.

Temperature susceptibility can be expressed quantitatively by various temperature susceptibility parameters. These parameters may be computed from test data obtained from routine quality control testing. None of these parameters is a true measure of the temperature susceptibility of asphalt because the measured properties which are used to determine each parameter include the visco-elastic effect as well as those of temperature.

Some of the most commonly accepted temperature susceptibility parameters are penetration index, penetration ratio and penetration viscosity number. They are briefly presented in the following paragraphs.

2.1.1 Penetration Index

Pfeiffer and van Doormaal (7) noted that the logarithm of the penetration was very nearly a linear function of temperature for the asphalt cements with which they had experienced. They developed a temperature susceptibility factor known as Penetration Index (PI), which is a function of the slope of the logarithm of penetration versus temperature relationship and is given by the following equation,

$$PI(dPen/dT) = \frac{20 - 500 * A}{50 * A + 1} \qquad [2.1]$$

where

$A = \frac{\log Pen @ T1 - \log Pen @ T2}{T1 - T2}$

T = Temperature (C)

Pen = Penetration 100 gm, 5 sec, (dmm)

Pfeiffer and van Doormaal further noted that the penetration of the asphalts which they investigated was about 800 dmm at the temperature corresponding to the softening point. This led to the proposal of an alternate equation for PI using the penetration at 25 C and the softening point as input parameters.

$$PI(R\&B) = \frac{20 - 500 * B}{50 * B + 1} \qquad [2.2]$$

where

$$B = \frac{\log 800 - \log Pen @ 25 C}{S.P. - 25}$$

S.P. = Ring & Ball Softening Point, (C)

Pen = penetration, 100 gm, 5 sec, (dmm)

It has subsequently been shown that the penetration of many asphalts at the softening point temperature differs substantially from 800 dmm and that the softening point of many Canadian asphalts is false due to the waxy crude oils from which they are produced (8). Therefore, Equation 2.2 is not a reliable way of calculating PI. Consequently, PI currently used by researchers is calculated using Equation 2.1 and penetration measurements at two temperatures.

Penetration index is a very important property of asphalt cement. It shows the temperature susceptibility of asphalt cement and can be used to estimate the stiffness modulus of asphalt cement at low temperatures from the nomograph developed by van der Poel. Large negative values of PI indicate greater temperature susceptibility and "typical" asphalts have values between +2 and -2.

2.1.2 Penetration Ratio

Several different penetration ratios have been proposed as measures of temperature susceptibility in the service temperature range. However, the commonly accepted (6) penetration ratio (PR) is defined as

$$PR = \frac{(\text{Pen @ 4 C, 200 gm, 60 sec.})}{(\text{Pen @ 25 C, 100 gm, 5 sec.})} * 100\% \qquad [2.3]$$

This ratio has been used, although infrequently, as a means of controlling temperature susceptibility in the low temperature region. Lower PR indicates greater temperature susceptibility.

2.1.3 Penetration Viscosity Number

McLeod (9) proposed a method for determining temperature susceptibility based on the penetration of asphalt cement at 25 C and its kinematic viscosity in centistokes at 135 C or its absolute viscosity in poise at 60 C. The parameter is known as the penetration viscosity number (PVN) and can be calculated from Equation 2.4 or 2.5 (6).

1. For the temperature range : 25 C to 135 C

$$PVN(25\text{-}135) = (-1.5) * \frac{4.258 - 0.7967 * \log P - \log X}{0.7951 - 0.1858 * \log P} \quad [2.4]$$

where

P = Pen at 25 C, dmm

X = Vis at 135 C, Centistokes

2. For the temperature range : 25 C to 60 C

$$PVN(25\text{-}60) = (-1.5) * \frac{6.489 - 1.590 * \log P - \log X}{1.050 - 0.2234 * \log P} \quad [2.5]$$

where

P = Pen at 25 C, dmm

X = Vis at 60 C, Poise

The PVN is an alternative to the penetration index as a temperature susceptibility parameter because PI(R&B) values for soft waxy asphalts calculated from their softening points and penetrations at 25 C are not consistent with their temperature susceptibilities in the low temperature region and with their resistance to thermally induced cracking. This discrepancy is caused by the presence of crystallizable components which increase the softening point to above the melting point of the crytalline phase (10,11).

The PVN value is intended to be numerically equal to the PI value so that it can be used to estimate low temperature stiffness modulus of asphalt cement and asphalt paving mixture from van der Poel's nomograph. However, several studies (12,13) have suggested that PVN and PI are not correlated and its use in estimating stiffness remains debatable.

Similar to PI, large negative values of PVN indicate greater temperature susceptibility and the range for "typical" asphalt cement is between +2 and -2.

2.2 Asphalt Stiffness

Asphalt stiffness, S(t,T), was first defined by van der Poel (14) as a means of characterizing asphalt consistency over a wide temperature range and in a form similar to Young's modulus given by the ratio of stress to strain in a tensile creep experiment:

$$S(t,T) = \frac{\sigma}{\epsilon(t,T)} \qquad [2.6]$$

where

$S(t,T)$ = Time and Temperature dependent Stiffness

σ = Tensile Stress

$\epsilon(t,T)$ = Time and Temperature dependent Strain

The total strain is a time and temperature dependent value induced by an uniform tensile stress. The resulting asphalt stiffness is a function of both the asphalt temperature and the time of loading, but it is independent of the loading stress.

Because asphalt stiffness has been found to correlate with low temperature pavement performance by many field and laboratory investigations and because it can be evaluated at low temperatures at which pavement cracking occurs, the principles of asphalt stiffness have been used as the basis for most recent low temperature design procedures (2).

Briefly, the principle incorporated in the stiffness concept involves controlling low temperature pavement transverse cracking by selecting the appropiate asphalt cement to ensure that the asphalt stiffness does not exceed a certain 'critical' or 'limiting' stiffness at the lowest pavement temperature.

2.2.1 Methods to Determine Asphalt Stiffness

There are basically two classes of approaches to determine low temperature stiffness of asphalt cement, i.e. direct testing and indirect estimation.

2.2.1.1 Direct Testing

Direct testing of asphalt is the most accurate method to evaluate low temperature asphalt stiffness. However, simple instruments capable of measuring asphalt stiffness at the required low temperature are not generally available. The penetration test has been the only practical method available for measuring low temperature rheology of paving asphalt. Recently, developments have made the measurement of asphalt stiffness close to the limiting stiffness value and at a temperature close to the pavement cracking possible (15). These instruments include:

1. Schweyer rheometer,
2. Shell Rheometer,
3. Ensley Forced Sphere,
4. Rheometrics mechanical spectrometer and
5. Duomorph.

2.2.1.2 Indirect Estimation

The indirect methods provide an estimate of stiffness without direct laboratory measurement. The methods use routine index test data and transform them into stiffness values using van der Poel's nomograph (Figure 2.2). The methods are simple and practical for routine low temperature pavement design purposes. Three commonly used methods, namely original van der Poel's method, Heukelom's modified method and McLeod's method are briefly presented as follows:

Van der Poel's Method

Van der Poel developed the stiffness nomograph such that a temperature susceptibility parameter "Penetration Index", and a consistency parameter "Ring and Ball Softening Point Temperature", characterized the rheological behaviour of asphalt over a wide range of temperatures and loading times (14).

The use of the nomograph, which is restricted to asphalts containing less than 2 percent by weight of wax, consists of the following steps:

1. Measure penetration at 25 C, 100g, 5 sec,
2. Measure softening point temperature, T(R&B)
3. Calculate penetration index, PI(R&B) according to Pfeiffer and van Doormaal's equation (Equation 2.2) by using 1) and 2),
4. Estimate stiffness, using the nomograph (Figure 2.2) with the loading time, the temperature difference between the desired temperature T and T(R&B) and PI(R&B) determined in 3) as input parameters.

Heukelom's Modified Method

Because of the false softening point of many asphalts due to the waxy crude oils from which they are produced, van der Poel's method of determining stiffness based on PI(R&B) may result in some very large error. As a result, Heukelom (10,11) developed a method which allows a 'corrected' softening point to be determined for waxy or blown asphalt. The modified method consists of the following steps:

1. Measure penetration at 25 C, 100g, 5 sec, and penetration at 4 C, 100g, 5 sec; plot the values on the Bitumen Test Data Chart (Figure 2.3),
2. Extend the line jointing the two penetrations down

to 800 pen and read off the temperature at 800 pen, T(800 pen),

3. Calculate PI(dPen/dT), using Equation 2.1 with values from 1),
4. Estimate stiffness, using van der Poel's nomograph (Figure 2.2) with loading time, the temperature difference between the desired temperature T and T(800 pen), and with PI(dPen/dT) determined in 3) as input parameters.

McLeod's PVN Method

McLeod has introduced the PVN as a parameter to measure the temperature susceptibility of asphalt and he uses this PVN as one of the input parameters to determine the stiffness of asphalt (9). The basic steps of McLeod's method are:

1. Measure penetration at 25 C, 100g, 5 sec and viscosity at 135 C,
2. Calculate PVN by using Equation 2.4,
3. Obtain the "base temperature", which is analogous to the ring and ball softening point temperature, from Figure 2.4 which is a modification by McLeod of a Pfeiffer and van Doormaal chart that was revised by Heukelom,
4. Estimate the stiffness, using the nomograph (Figure 2.5) with the loading time, the temperature

difference between the desired temperature and the base temperature from 3), and PVN determined from 2) as input parameters. The nomograph, Figure 2.5, which was modified by McLeod, is very similar to the original van der Poel's nomograph.

2.2.2 Comparison of Various Methods

The methods of estimating asphalt stiffness and evaluating temperature susceptibility as described in the previous sections have been used by many investigators and have been quite controversial. The PI(R&B) developed by Pfeiffer and van Doormaal assumes that the penetration of an asphalt at its softening point is 800, which is incorrect for some waxy Canadian asphalts. Kopvillem and Heukelom (11) modified the method of determining PI which required penetration values at two temperatures.

McLeod, for the same reasons, developed a pen-vis-number based on penetration at 25 C and Viscosity at 135 C. He compared the PI(R&B) and PVN of 300 normal asphalt cements and concluded that PVN was an improvement over PI(R&B).

Haas (16), in his research report for the Asphalt Institute, compared various methods of stiffness determination and recommended McLeod's method of using PVN in his prediction model of low temperature transverse cracking.

Kandhal (17), in his studies of low temperature transverse cracking of pavement in Pennsylvannia, also compared the three methods. He found that PVN correlated to PI(R&B) and was a better indicator of temperature susceptibility.

Noureldin and Manke (18), in their studies of pavements in Oklahoma, also found that transverse cracking of the pavements was related to stiffness modulii determined by an indirect method using PVN.

The use of PI as a temperature susceptibility parameter and for estimation of asphalt cement stiffness has also been recommended by several other researchers. Robertson (13), in his comparision of PI(dPen/dT), PR and PVN as indices of temperature susceptibility, concluded that PI(dPen/dT) and PR were the best indicators of temperature susceptibility in the low temperature range and that PVN did not correlate well with low temperature behaviour of asphalt cement.

Gaw, (2) in his latest Asphalt Institute report (1981), compared the PI(dPen/dT) procedures and the PVN procedures for predicting asphalt stiffness, directly with measured asphalt stiffness. He concluded that both PI and PVN procedures gave reasonable results for non-waxy asphalt at moderate low temperatures and that the PI procedures gave the most accurate stiffness prediction for both waxy and air blown asphalt.

From the above review, it is obvious that there is a wide divergence of methods in estimating stiffness of asphalt. However, the use of van der Poel's nomograph is the same for all methods. In this research, both the PI(R&B), PI(dPen/dT) and McLeod's method will be used.

2.3 Asphalt Mixture Stiffness

The methods of measuring asphalt mixture stiffness consist of tension or compression test by creep, relaxation or constant rate of strain testing, and dynamic or flexural testing. The two tests most widely reported for establishing low temperature response are the constant rate of extension, direct uni-axial tension testing which has been developed at the University of Waterloo; and the indirect tensile splitting test which is used at the University of Alberta (16,19). The indirect tensile splitting test, which is used in this research, is discussed in detail in Chapter VI and Appendix D.

2.4 Cracking Temperature

The temperature at which pavement starts to crack, termed 'pavement cracking temperature', is a more direct indication of the pavement's relative performance in low temperature. The cracking temperature can be calculated based on the asphalt stiffness by the concept of limiting or critical stiffness, the concept of limiting stress, and the nomographic method. The cracking temperature determined by these methods assumes that asphalt properties are the major influence on pavement transverse cracking neglecting the influence of other factors such as asphalt content, air voids content and aggregate properties etc.

2.4.1 Limiting Asphalt Stiffness Method

Pavement cracking temperature can be determined by estimating the temperature at which the asphalt reaches a certain 'limiting' stiffness. Different investigators have used different values of limiting stiffness at different time of loading. However, the most frequent used and adopted limiting stiffness of asphalt cement is 1 X 10^9 N/m^2 at 1800 sec loading time, which is based on observations from the Ste. Anne road test (5,15).

The procedures for estimating cracking temperature require the use of either PI or PVN as one of the input parameters. Details are as follows:

1. Determine PI(dPen/dT) or PVN depending on which index is used,
2. Establish the point on the stiffness modulus of van der Poel's nomograph (Figure 2.2 or 2.5) for a stiffness of 1 X 10^9 N/m^2 at the appropriate PI or PVN level,
3. Draw a straight line between 1 X 10^9 N/m^2 point and the half hour point on the time of loading scale,
4. The temperature difference at the point of intersection of the line from step 3 and the temperature difference scale is recorded as T(diff),
5. The (limiting stiffness) cracking temperature, T_{ls} is

obtained by Equation 2.7,

$$T_{1s} = T(800\ pen) - T(diff) \qquad [2.7a]$$

or

$$T_{1s} = T(base) - T(diff) \qquad [2.7b]$$

where

T(800 pen) is the temperature at 800 penertration when using PI(dPen/dT),

T(base) is the base temperature obtained by using McLeod's modified nomograph (Figure 2.4).

2.4.2 Limiting Asphalt Stress Method

Hills (20) introduced a procedure for determining predicted cracking temperature of pavement based on an estimation of thermal stress developed in the asphalt. He assumed that the thermal stress, σ_t developed in asphalt due to cooling can be calculated from:

$$\sigma_t = \Sigma\ S_i * a_a * \Delta T \qquad [2.8]$$

where

S_i is the asphalt stiffness at one hour loading time at a series of temperature intervals ΔT apart.

a_a is the coefficient of linear contraction.

Hills further concluded from semi-theoretical considerations and from mix cracking observations that pavement cracking occurred at a temperature corresponding to a calculated thermal stress of 5 x 10^5 N/m^2.

The procedures of estimating cracking temperature using limiting stress method are as follows:

1. Estimate asphalt stiffness at one hour loading time at a series of temperature intervals,
2. Determine thermal stress due to cooling using Equation 2.8 at each interval,
3. Plot temperature versus total thermal stress induced by cooling,
4. Obtain the cracking temperature from the curve at a point corresponding to 5 x 10^5 N/m^2.

The limiting stress approach has been used by Christison in his psuedo-elastic beam or slab analysis (21), which was used as a basis for the distress prediction model called COLD program (COmputation of Low temperature Damage)(22).

2.4.3 Nomographic Method

The cracking temperature of asphalt can be estimated from two penetrations by using the nomograph shown in Figure 2.6. This nomograph was developed by Gaw (23). It is based on the fact that there is a unique relationship between asphalt penetration at 25 C and 5 C and the calculated cracking temperature.

The use of the nomograph is simple and the procedures are as follows:

1. Enter the appropriate values of penetration at 25 C and penetration at 5 C into Figure 2.6 and obtain the predicted cracking temperature,
2. If the penetration has been determined at a temperature other than 25 C and 5 C, extrapolate the data to 25 C and 5 C by using a semi-logarithmic plot.

2.4.4 Fracture Temperature

Recently, a testing technique to measure temperature induced stress and fracture temperature of asphalt concrete mixtures has been developed in Hokkaido University of Japan (28,29). The technique consists of measuring the load induced on a constrained rectangular asphalt concrete specimen, which is subjected to cooling at a programmed cooling rate. The temperature at which the specimen fails is termed fracture temperature. This fracture temperature is found to correlate with asphalt properties, particularly penetration and temperature susceptibility.

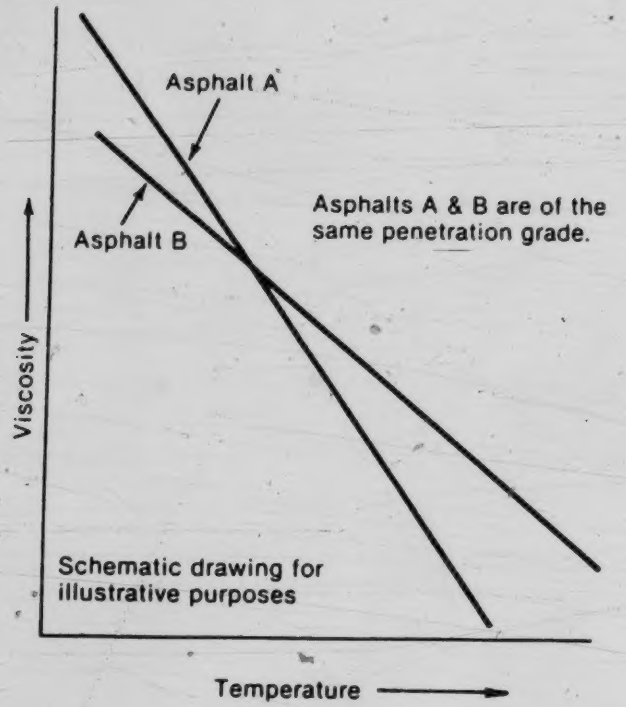
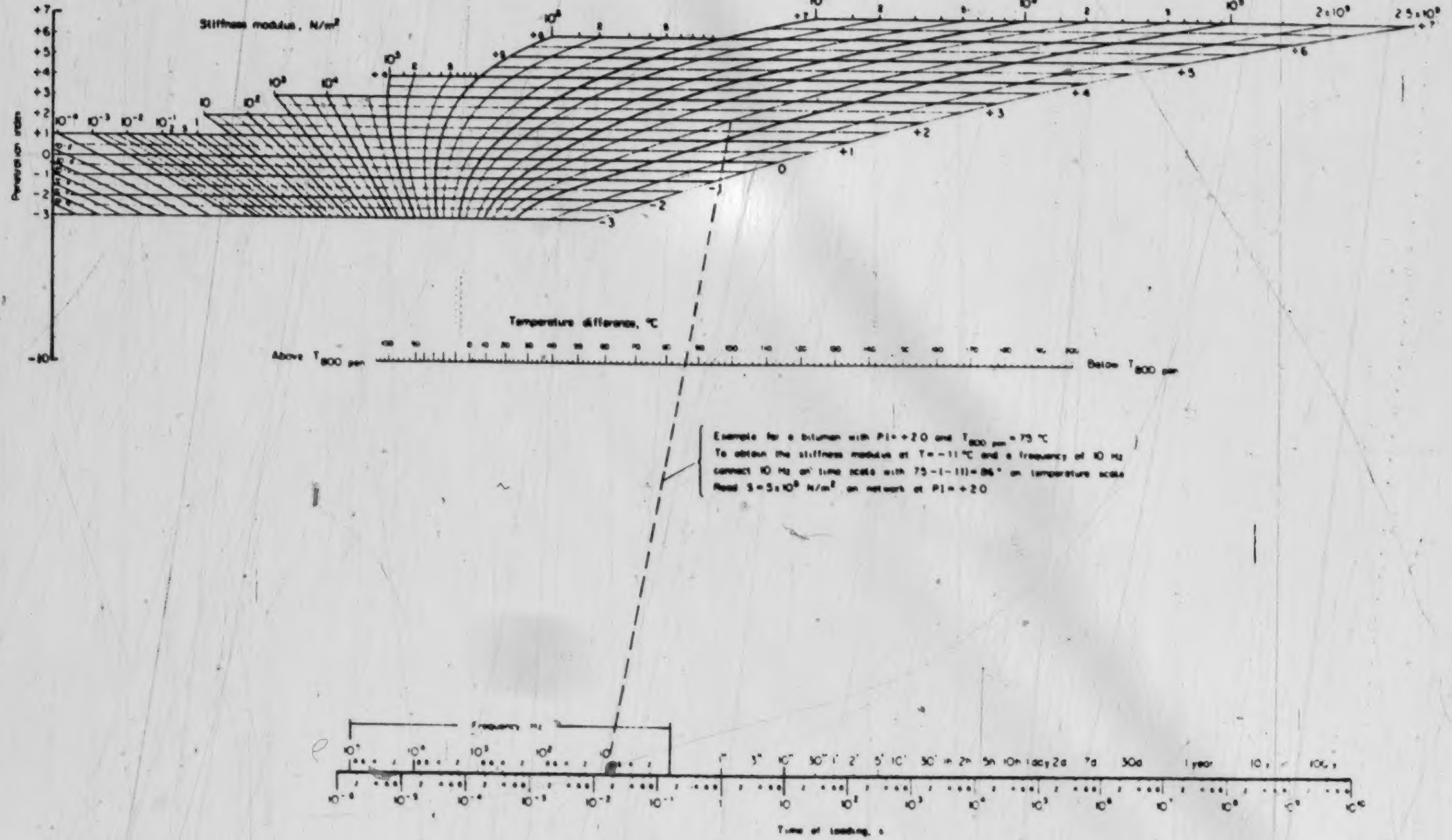


Figure 2.1 Variation in Viscosity of two Penetration Graded Asphalts



Example for a bitumen with PI = +2.0 and $T_{800\ pen}$ = 73 °C
To obtain the stiffness modulus at T = −11 °C and a frequency of 10 Hz
connect 10 Hz on time scale with 75 − (−11) = 86° on temperature scale
Read $S = 5 \times 10^8$ N/m² on network at PI = +2.0

Figure 2.2 Nomograph for Determining the Stiffness Modulus of Bitumens

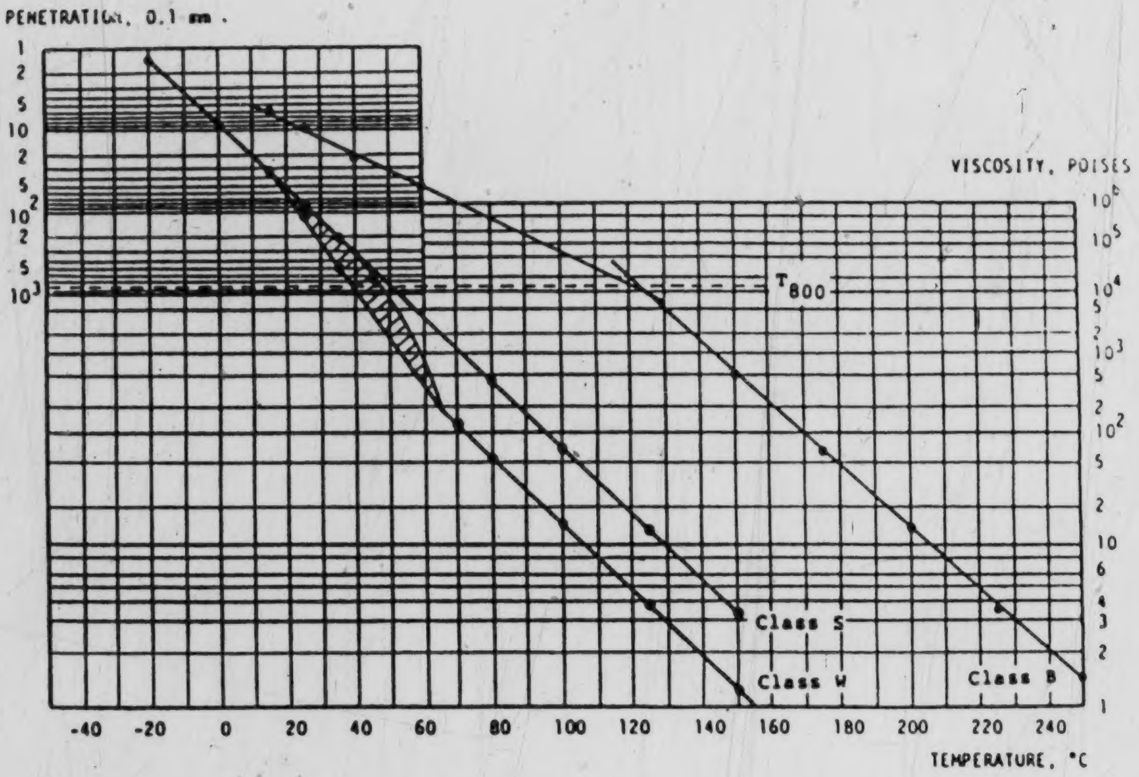
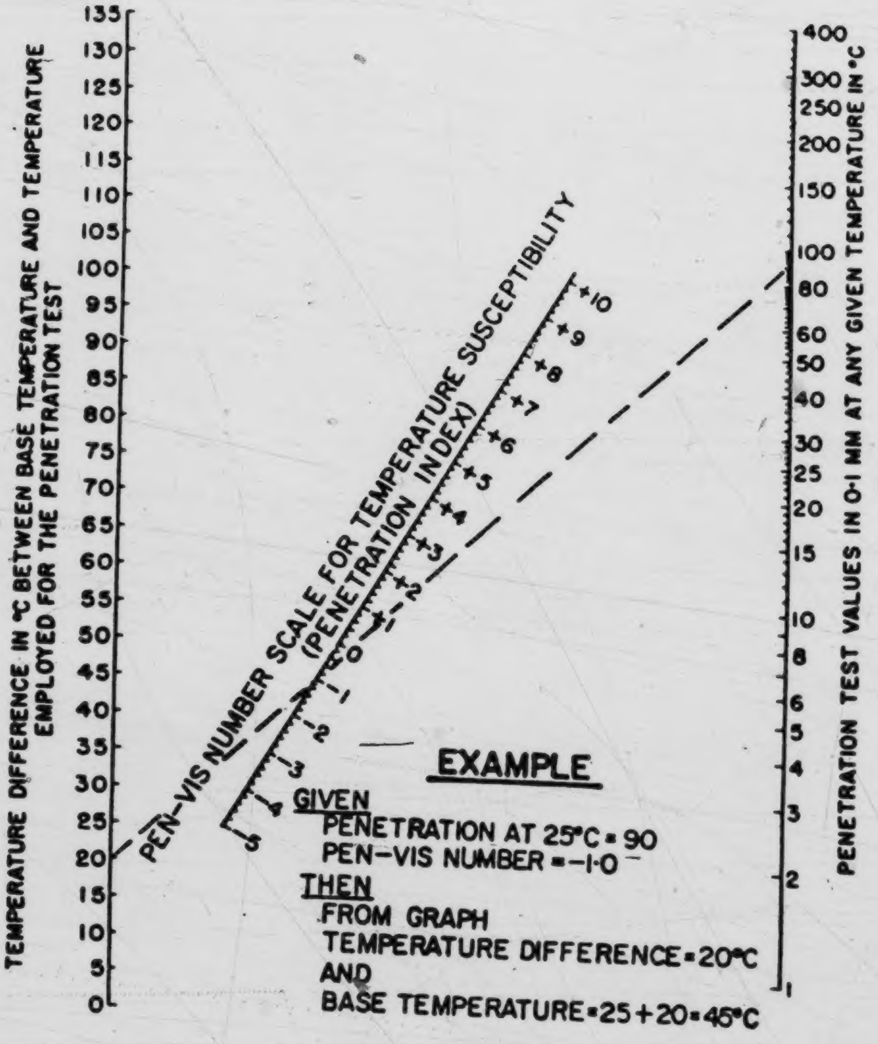


Figure 2.3 Bitumen Test Data Chart for Class S (Straight-Run), Class B (Blown), and Class W (Waxy) Asphalts



EXAMPLE

GIVEN
PENETRATION AT 25°C = 90
PEN-VIS NUMBER = -1·0
THEN
FROM GRAPH
TEMPERATURE DIFFERENCE = 20°C
AND
BASE TEMPERATURE = 25 + 20 = 45°C

Figure 2.4 Relationship between Penetration, PVN and Base Temperature

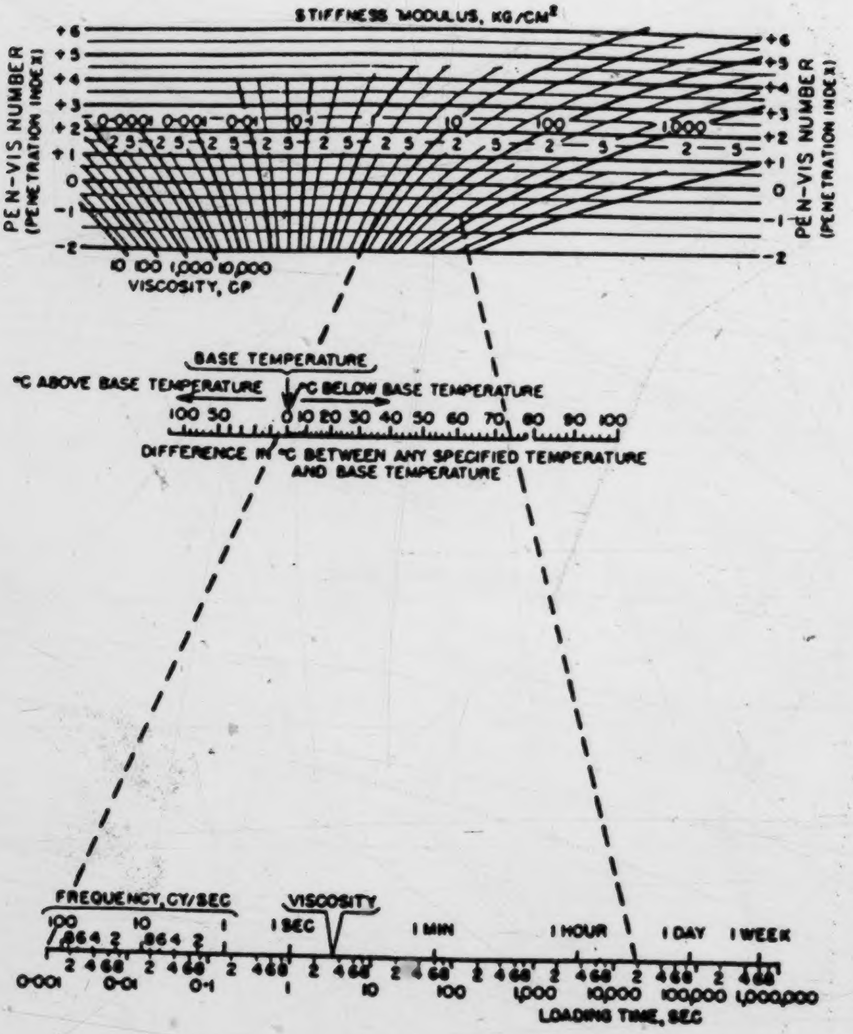


Figure 2.5 Nomograph for Determining the Stiffness Modulus of Asphalts

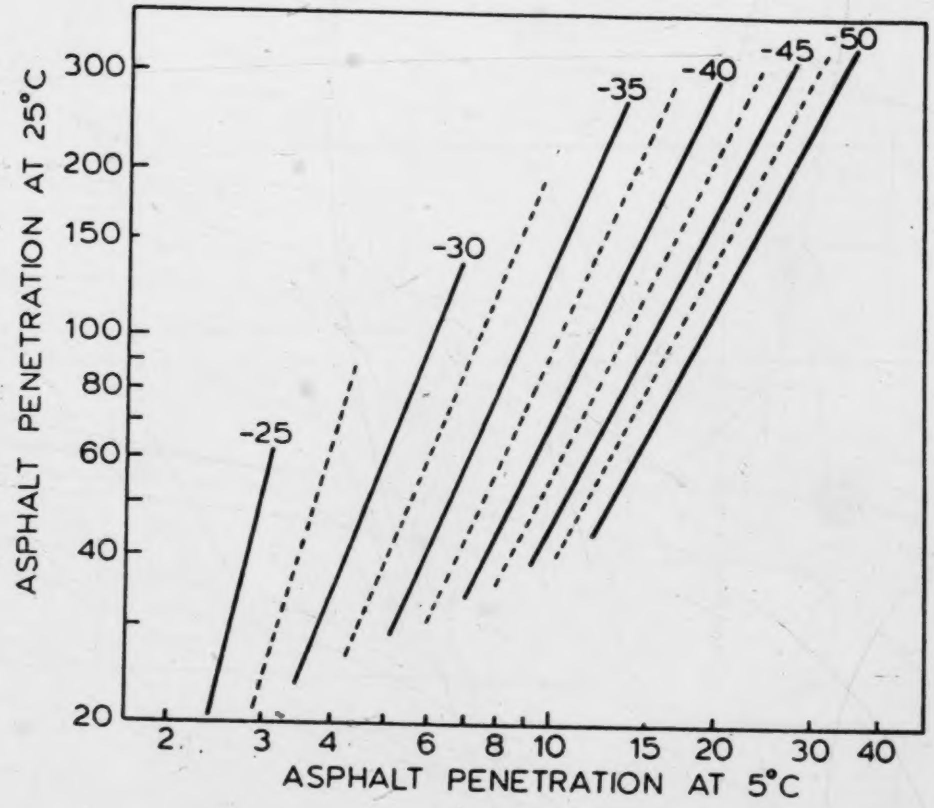


Figure 2.6 Nomograph for Predicting Cracking Temperatures

3. PROPERTIES OF ALBERTA ASPHALT CEMENT

3.1 General

In order to obtain a perspective view of the properties of asphalt cements that have been used in road construction in Alberta, historical routine test data on asphalt cements supplied to Alberta Transportation in the year 1979 and 1984 were obtained and analyzed. These data represented eight grades of road construction asphalt cements from five refineries in western Canada prior to and after the change of asphalt specification in 1980. The 1979 data set was the earliest data set available in Alberta Transportation's computerized data bank; whereas the 1984 data set was the latest data set at the beginning of this study.

The tests were performed by the Alberta Transportation laboratory. The data sets consist of test results of 592 and 581 samples in 1984 and 1979 respectively. The 1984 data set consisted of grade 150/200A, 200/300A, 300/400A and 200/300B, and the 1979 data set consisted of grade 150/200, AC60.0, AC27.5, AC20.0 and AC1.5. The five refineries were Gulf Oil of Moose Jaw, Gulf Oil of Calgary, Husky Oil of Lloydminster, Imperial Oil of Edmonton and Shell of Three Creeks.

The properties analyzed included the penetration and viscosity of both the original and after thin film oven tested asphalts(TFOT). Temperature susceptibility parameters, for example, the 'Penetration Viscosity Number

(PVN)', were computed using equations given in chapter 2. The effect of TFOT on the asphalts was also analyzed by computing several parameters such as 'retained penetration', 'viscosity ratio' and PVN after TFOT. The test data and the parameters computed were statistically analyzed to determine their means, standard deviation and coefficient of variation for each refinery and grade. The maximum and minimum values of the data and parameters were also included in order to give an idea of the range and variability of the properties.

The summary of the test data and computed parameters are presented in Appendix A according to grades and sources. The test data and parameters are also presented in graphical form by various plots. The plots are contained in Appendix B.

3.2 1984 test data

3.2.1 Grade 150/200A

Three refineries produced this grade of asphalt in 1984. They were Gulf Oil of Moose Jaw, Husky Oil of Lloydminster and Imperial Oil of Edmonton. The number of test data from each refinery were 8, 147 and 113 respectively. (Table 3.1)

1. The mean penetration and viscosity values of the Husky and Imperial asphalts are similar. However, the values of the Gulf asphalt are much higher. The mean penetration value of the Gulf asphalt is actually

outside the acceptable range of 150 to 200 for this grade of asphalt. This is probably due to some extreme test results and the small number of samples tested.

2. All the asphalts have low temperature susceptibility as indicated by the PVNs. The asphalts from Imperial have the largest negative PVN, that is, the most temperature susceptible among the three asphalts. However, the difference is small. There is only a maximum numerical difference of 0.23 between the Imperial and Gulf asphalts. The values of the PVN of the Husky and Gulf asphalts are similar.
3. The Gulf asphalts became more temperature susceptible after the TFOT as shown by the values of PVN before TFOT (PVN(25-60)) and PVN after TFOT (TFPVN(25-60)). The PVN(25-60) of the Husky and Imperial asphalts has remained relatively unchanged after the TFOT.
4. The asphalts produced by Husky seem to show less change following the TFOT than the other two asphalts. This can be observed by comparing the value of the loss of weight after TFOT. This suggestion is further supported by comparing the ratio of retained penetration and ratio of viscosity after TFOT.
5. By comparing the coefficient of variation (C.V. %) of the penetration values and viscosity values, it is noted that the asphalts produced by Husky and Imperial have smaller variation than the asphalts produced by Gulf. The higher coefficient of variation of the Gulf asphalts

is again probably due to their smaller number of samples tested.

3.2.2 Grade 200/300A

Three refineries produced this grade of asphalt in 1984. They were Husky Oil of Lloydminster, Imperial Oil of Edmonton and Gulf Oil of Moose Jaw. However, the test data of the asphalts from Gulf Moose Jaw were not analyzed because there were only three samples tested. The number of test data from Husky and Imperial were 120 and 168 respectively. (Table 3.2)

1. By comparing the values of the penetration at 25 C alone, it is noted that the asphalts from Husky are softer than that from Imperial. However, the viscosity values are similar.
2. Both the PVN(25-60) and PVN(25-135) of the Husky asphalts have smaller negative values than that of the Imperial asphalts. This indicates that the Husky asphalts ~~are~~ slightly less temperature susceptible.
3. Both the Husky and Imperial asphalts became more temperature susceptible after the TFOT.
4. The weight loss, ratio of retained penetration and viscosity after TFOT all show that the Husky asphalts have slightly higher resistance to heating and aging than the Imperial asphalts.
5. The variation of penetration and viscosity of the Imperial asphalts are slightly higher than that of the

Husky asphalts. This is indicated by the slightly higher coefficient of variation.

3.3 1979 test data

3.3.1 Grade 150/200

Only two refineries produced this grade of asphalt in 1979. They were Gulf Oil of Moose Jaw and Imperial Oil of Edmonton. The number of test data from each refinery were 21 and 35 respectively. (Table 3.3)

1. The mean penetration and viscosity of both the Gulf and Imperial asphalts are similar.
2. The PVN(25-135) of the asphalts of both refineries are similar. However, the PVN(25-60) and TPVN(25-60) of the Imperial asphalts are slightly more negative than that of the Gulf asphalts. It is noted that the PVNs of this grade of asphalt are relatively more negative than the other grades of asphalts indicating that this grade of asphalt is more temperature susceptible.
3. The change of weight of the Imperial asphalt following the TFOT is very little. The asphalt also has low viscosity ratio and high retained penetration.
4. The variation of the properties of the Imperial asphalts is greater than that of the Gulf product. This is indicated by the difference of the coefficient of variation.

3.3.2 Grade AC-60.0

Four refineries produced this grade of asphalt in 1979. They were Husky Oil of Lloydminster, Imperial Oil of Edmonton, Gulf Oil of Calgary and Gulf Oil of Moose Jaw. However, test data of Gulf Moose Jaw were not considered because of the small number of tests done. The number of test data from Husky, Imperial and Gulf Calgary were 18, 65 and 29 respectively. (Table 3.4)

1. This group of asphalt is equivalent to the present 150/200A asphalt and has a range of penetration at 25 C from 170 to 182.
2. The Husky asphalts have a slightly higher mean viscosity at both 135 C and 60 C than the Imperial and Gulf Calgary asphalts.
3. The PVN(25-60) and PVN(25-135) of the Husky asphalts have the smallest negative values indicating that the Husky asphalts are less temperature susceptible than the other two asphalts.
4. The TFOT has the effect of changing all the asphalts to become more temperature susceptible as indicated by comparing the PVN(25-60) and TPVN(25-60).
5. All the three asphalts have a similar retained penetration after the TFOT. However, the Gulf asphalts have a very small viscosity ratio and weight loss due to TFOT than the other two asphalts.
6. The Husky asphalts have a much greater variation in the penetration and viscosity values than the other two.

3.3.3 Grade AC-27.5

Three refineries produced this grade of asphalt in 1979. They were Husky Oil of Lloydminster, Imperial Oil of Edmonton and Gulf Oil of Calgary. The number of test data from each refinery were 126, 241 and 10 respectively. (Table 3.5)

1. This viscosity graded asphalt is equivalent to the present 200/300A grade asphalt and has penetration values ranging from 276 to 291.
2. The Husky asphalts have a higher mean viscosity at both 60 C and 135 C when comparing to the Gulf and Imperial asphalts. The Husky asphalts also have the lowest penetration at 25 C.
3. The PVN(25-60), PVN(25-135) and PVN(25-60) after TFOT, of the Husky asphalts have the smallest negative value indicating that the asphalts are the least temperature susceptible among the three asphalts.
4. All the three asphalts have become more temperature susceptible after TFOT.
5. The Gulf asphalts have the smallest weight loss, smallest viscosity ratio and highest retained penetration after TFOT among the three asphalts. This indicates that the Gulf asphalts are less affected by aging and hardening. On the contrary, the Husky asphalts have a higher weight loss and viscosity ratio after the TFOT indicating that they are more vulnerable to aging and hardening.

6. The Husky asphalts have a slightly smaller coefficient of variation of the penetration and viscosity values.

3.4 Summary

The properties of the asphalts produced in 1984 and 1979 by various refineries are best represented in plots of mean values of various properties as shown in Figure 3.1a to 3.1e and 3.2a to 3.2e. Plots of individual test data points are contained in Appendix B. The ranking of the asphalts by refineries is rated in Table 3.6 and the variability of the properties of the 1984 and 1979 asphalts are tabulated in Table 3.7 and 3.8.

In ranking the asphalts, the following are considered as desirable products for use in pavement construction: asphalts with low temperature susceptibility, as indicated by the PVN; asphalts with high durability, as shown by the minimal percent weight loss, low viscosity ratio and high retained penetration; and asphalts of uniform properties, as indicated by the coefficient of variation.

Most of the asphalts produced in 1984 meet the premium grade requirements of the 1980 Alberta Transportation Specification for Asphalt Cements' The Shell Three Creeks' product is marginally outside the premium grade specified limits and is classified as regular grade.

Despite meeting the specification, asphalt properties did vary among different refineries. The 1984 test data

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' For details of the specification, see Chapter 4 shows that in general, the asphalts produced by Husky have more uniform properties and are more durable than the other asphalts produced by other refineries. The Husky asphalts are also the least temperature susceptible.

Most of the asphalts produced in 1979 also would have met or exceeded the 1980 specification requirements for the regular grade, with the Husky and most of the Imperial asphalts particularly, complying with the requirements for the premium grade. However, because the specification in 1979 was somewhat less stringent, there was a greater variation in the 1979 asphalt properties. The 150/200 grade asphalt, which did not have a viscosity requirement, was considerably more temperature susceptible than the others.

The 1979 test data shows that in general, the asphalts produced by Husky are more viscous at high temperatures and consequently less temperature susceptible than the asphalts produced by Gulf and Imperial. However, the Husky asphalts are more vulnerable to weight loss due to TFOT. The Gulf asphalts, particularly the AC 60.0 and AC 27.5 grade, seem to have better resistance to TFOT aging and heating. The Gulf 150/200 grade asphalts exhibit results to the contrary. They have low retained penetration and high viscosity ratio even though their weight loss due to TFOT remains low.

Table 3.1 Properties of Asphalt - 1984 Pen 150/200A

Properties	Refineries		
	Gulf	Husky	Imperial
Pen 25 C (dmm) (C. V. %)	208 (23)	169 (7)	160 (7)
Vis 60 C (Pa.s) (C. V. %)	67.3 (22)	81.5 (5)	80.0 (10)
Vis 135C (Cst.) (C. V. %)	238 (11)	273 (8)	259 (7)
PVN(25-60)	-0.00	-0.11	-0.23
PVN(25-135)	-0.18	-0.19	-0.35
TFPVN(25-60)	-0.15	-0.14	-0.24
% Wt. Loss	0.60	0.31	0.55
Vis Ratio	2.80	2.30	2.76
Retained Pen	0.50	0.58	0.51

Table 3.2 Properties of Asphalt - 1984 Pen 200/300A

Properties	Refineries	
	Husky	Imperial
Pen 25 C (dmm) (C. V. %)	276 (6)	234 (7)
Vis 60 C (Pa.s) (C. V. %)	42.6 (7)	44.6 (13)
Vis 135 C (Cst.) (C. V. %)	201 (6)	199 (8)
PVN(25-60)	+0.05	-0.22
PVN(25-135)	-0.05	-0.31
TFPVN(25-60)	-0.07	-0.37
% Wt. Loss	0.61	0.71
Vis Ratio	2.46	2.65
Retained Pen	0.53	0.49

Table 3.3 Properties of Asphalt - 1979 Pen 150/200

Properties	Refineries	
	Gulf	Imperial
Pen 25 C (dmm) (C. V. %)	174 (6)	178 (15)
Vis 60 C (Pa.s) (C. V. %)	48.0 (6)	43.2 (15)
Vis 135 C (Cst.) (C. V. %)	198 (2)	200 (9)
PVN(25-60)	-0.67	-0.78
PVN(25-135)	-0.70	-0.68
TFPVN(25-60)	-0.66	-0.88
% Wt. Loss	0.28	0.09
Vis Ratio	2.88	1.91
Retained Pen	0.50	0.62

Table 3.4 Properties of Asphalt -1979 AC 60.0

Properties	Refineries		
	Gulf	Husky	Imperial
Pen 25 C (dmm) (C. V. %)	182 (10)	181 (33)	170 (5)
Vis 60 C (Pa.s) (C. V. %)	62.3 (11)	83.0 (19)	73.4 (6)
Vis 135 C (Cst.) (C. V. %)	234 (10)	267 (17)	247 (5)
PVN(25-60)	-0.29	-0.04	-0.21
PVN(25-135)	-0.36	-0.20	-0.35
TFPVN(25-60)	-0.39	-0.11	-0.25
% Wt. Loss	0.18	0.55	0.38
Vis Ratio	2.19	2.41	2.49
Retained Pen	0.58	0.56	0.55

Table 3.5 Properties of Asphalt - 1979 AC 27.5

Properties	Refineries		
	Gulf	Husky	Imperial
Pen 25 C (dmm) (C. V. %)	288 (10)	276 (5)	291 (8)
Vis 60 C (Pa.s) (C. V. %)	31.5 (7)	43.3 (7)	34.5 (10)
Vis 135 C (Cst.) (C. V. %)	165 (5)	200 (4)	174 (8)
PVN(25-60)	-0.26	+0.08	-0.12
PVN(25-135)	-0.37	-0.05	-0.25
TFPVN(25-60)	-0.39	-0.08	-0.31
% Wt. Loss	0.25	0.86	0.63
Vis Ratio	2.31	2.55	2.41
Retained Pen	0.56	0.51	0.52

Table 3.6 Ranking of Asphalts by Refineries in Decreasing Order of Desirability[1]

Properties	1984		1979		
	150/200A	200/300A	150/200	AC 60.0	AC 27.5
Temperature Susceptibility (PVN25-135)	Gulf* Husky* Imperial	Husky Imperial	Gulf* Imperial*	Husky Imperial* Gulf*	Husky Imperial Gulf
Resistance to TFOT	Husky Imperial* Gulf*	Husky Imperial	Imperial Gulf	Gulf Imperial* Husky*	Gulf Imperial Husky
Variability	Husky* Imperial* Gulf	Husky Imperial	Gulf Imperial	Imperial Gulf Husky	Husky Gulf* Imperial*

* Rating is close

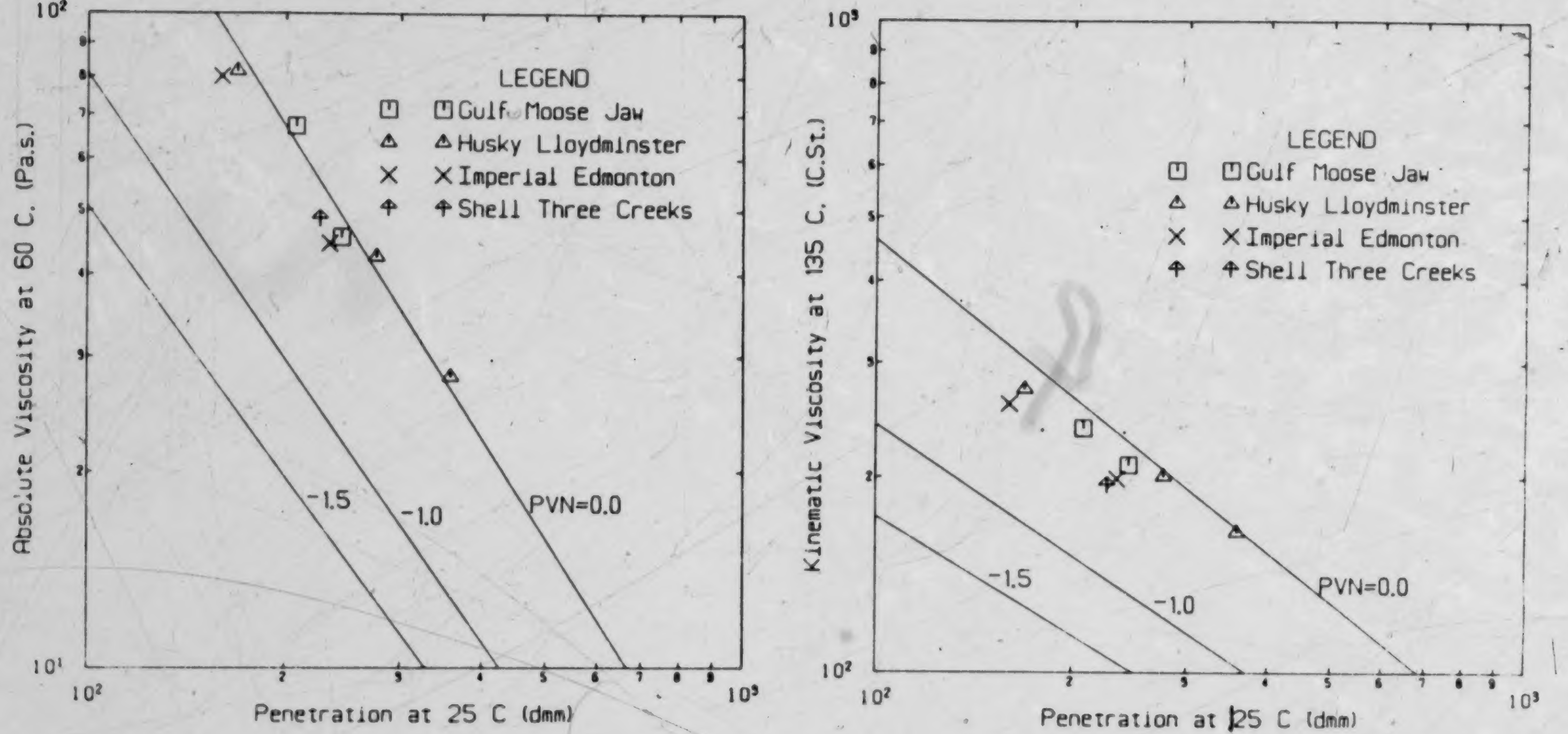
[1] Low temperature susceptibility, high resistance to TFOT and small variability are considered as desirable asphalt properties for pavement construction.

Table 3.7 Variability of the Properties of the 1979 Asphalts

Parameters	Gulf Moose Jaw (min - max)	Gulf Calgary (min - max)	Husky Lloydminster (min - max)	Imperial Edmonton (min - max)
PVN(25-60)	-0.66 - -0.09	-0.65 - -0.06	-0.51 - +0.33	-1.15 - +0.00
PVN(25-135)	-0.81 - -0.20	-0.51 - +0.29	-1.04 - +0.42	-1.66 - +0.56
TFPVN(25-60)	-0.86 - -0.14	-0.47 - -0.32	-1.02 - +0.59	-1.17 - +0.16
% Wt. Loss	0.19 - 0.61	0.05 - 1.38	0.36 - 1.95	0.01 - 1.84
Retained Pen	0.41 - 0.85	0.34 - 0.64	0.26 - 0.80	0.38 - 0.78
Vis Ratio	1.63 - 3.84	1.91 - 3.95	1.94 - 3.89	1.57 - 3.64

Table 3.8 Variability of the Properties of the 1984 Asphalts

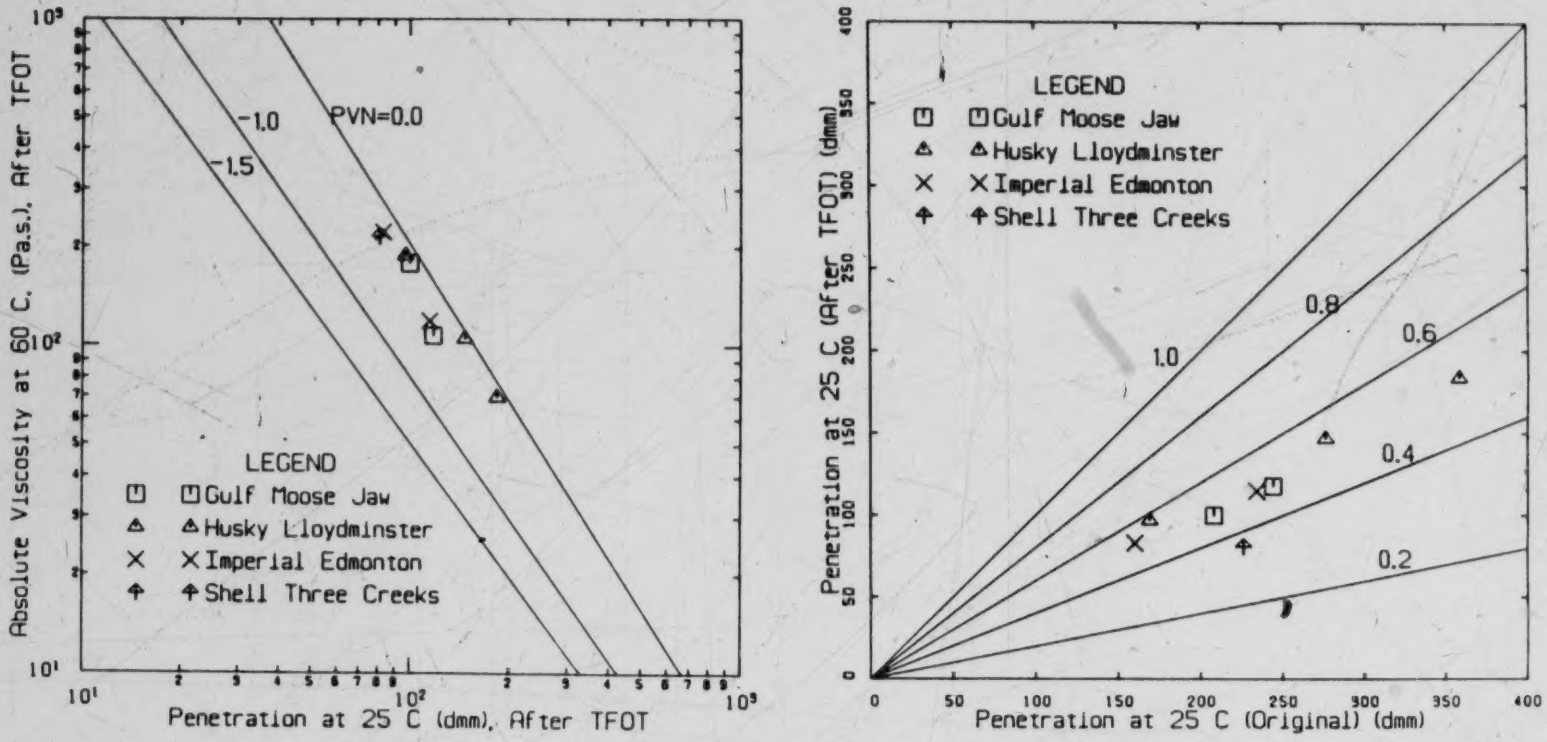
Parameters	Gulf Moose Jaw (min - max)	Husky Lloydminster (min - max)	Imperial Edmonton (min - max)	Shell Three Creeks (min - max)
PVN(25-60)	-0.13 - +0.18	-0.33 - +0.61	-0.49 - +0.24	-0.05 - -0.35
PVN(25-135)	-0.25 - +0.03	-0.70 - +0.29	-0.79 - +0.21	-0.29 - -0.60
TFPVN(25-60)	-0.42 - -0.10	-0.42 - +0.35	-0.59 - +0.05	-0.04 - -0.42
% Wt. Loss	0.32 - 1.96	0.07 - 1.57	0.31 - 1.32	1.84 - 3.91
Retained Pen	0.32 - 0.55	0.42 - 0.74	0.38 - 0.58	0.29 - 0.44
Vis Ratio	2.13 - 4.85	1.57 - 3.25	1.96 - 4.05	3.48 - 5.79



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

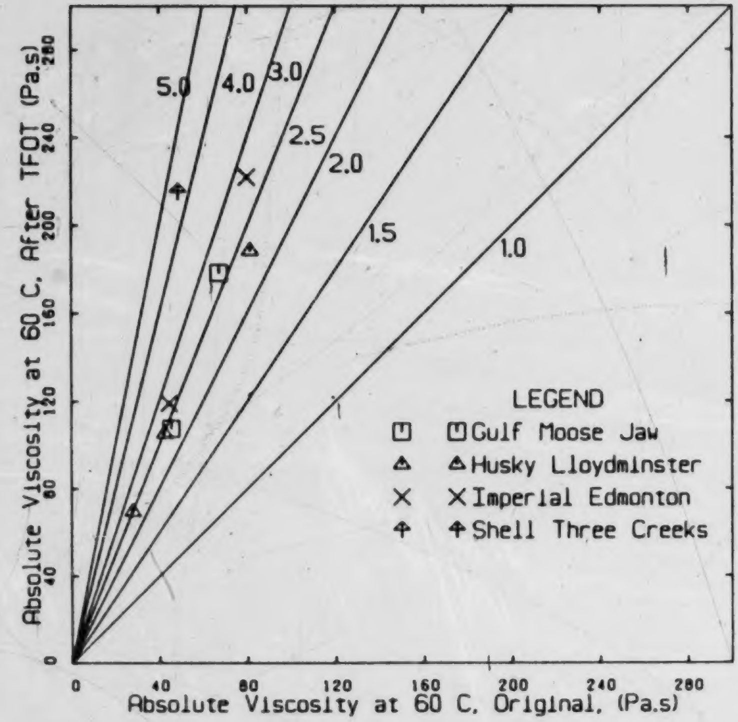
Figure 3.1 Comparison of Mean 1984 Asphalt Properties by Refineries



(c) TPen 25 C versus TVis 60 C

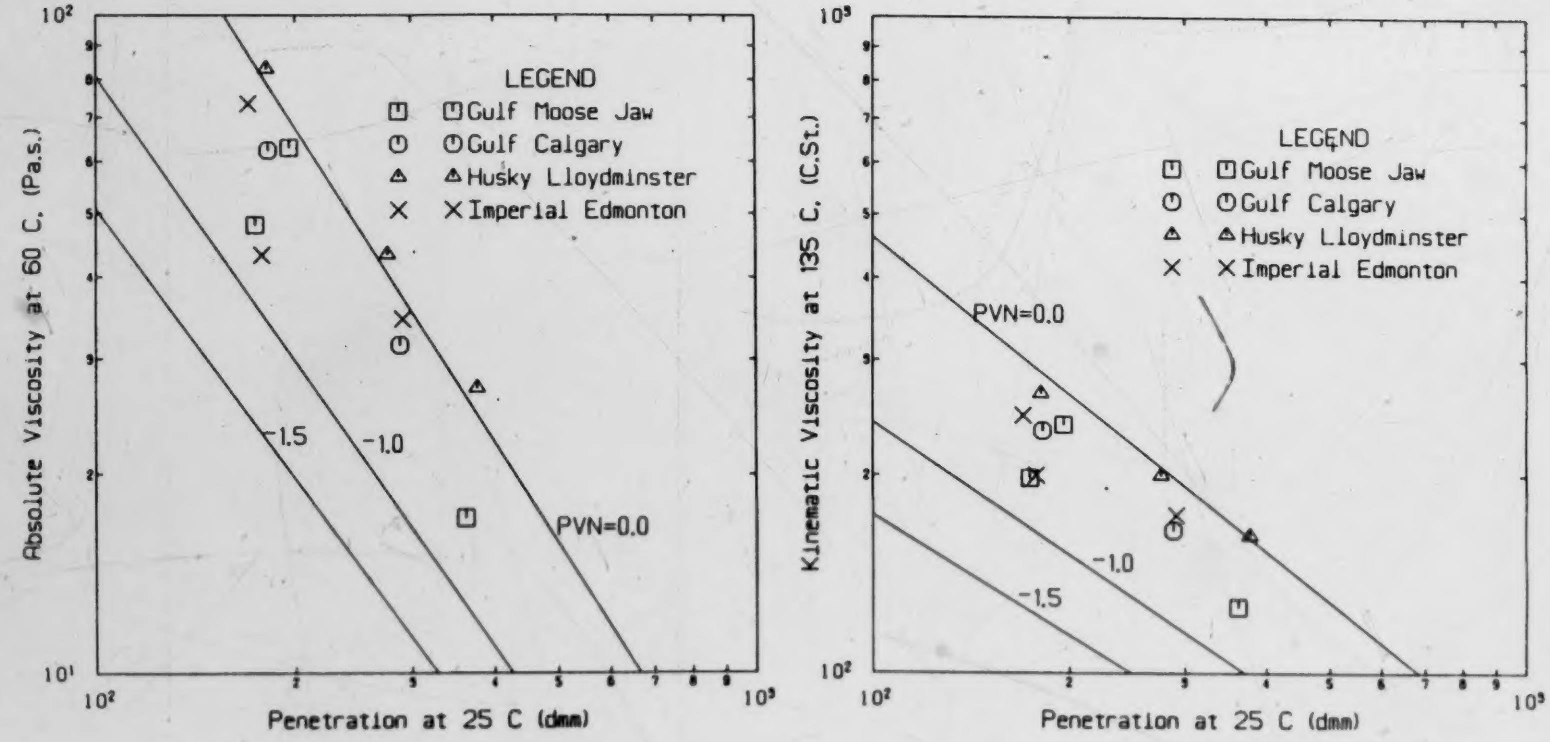
(d) Pen 25 C versus TPen 25 C

Figure 3.1 Comparison of Mean 1984 Asphalt Properties by Refineries



(e) Vis 60 C versus TVis 60 C

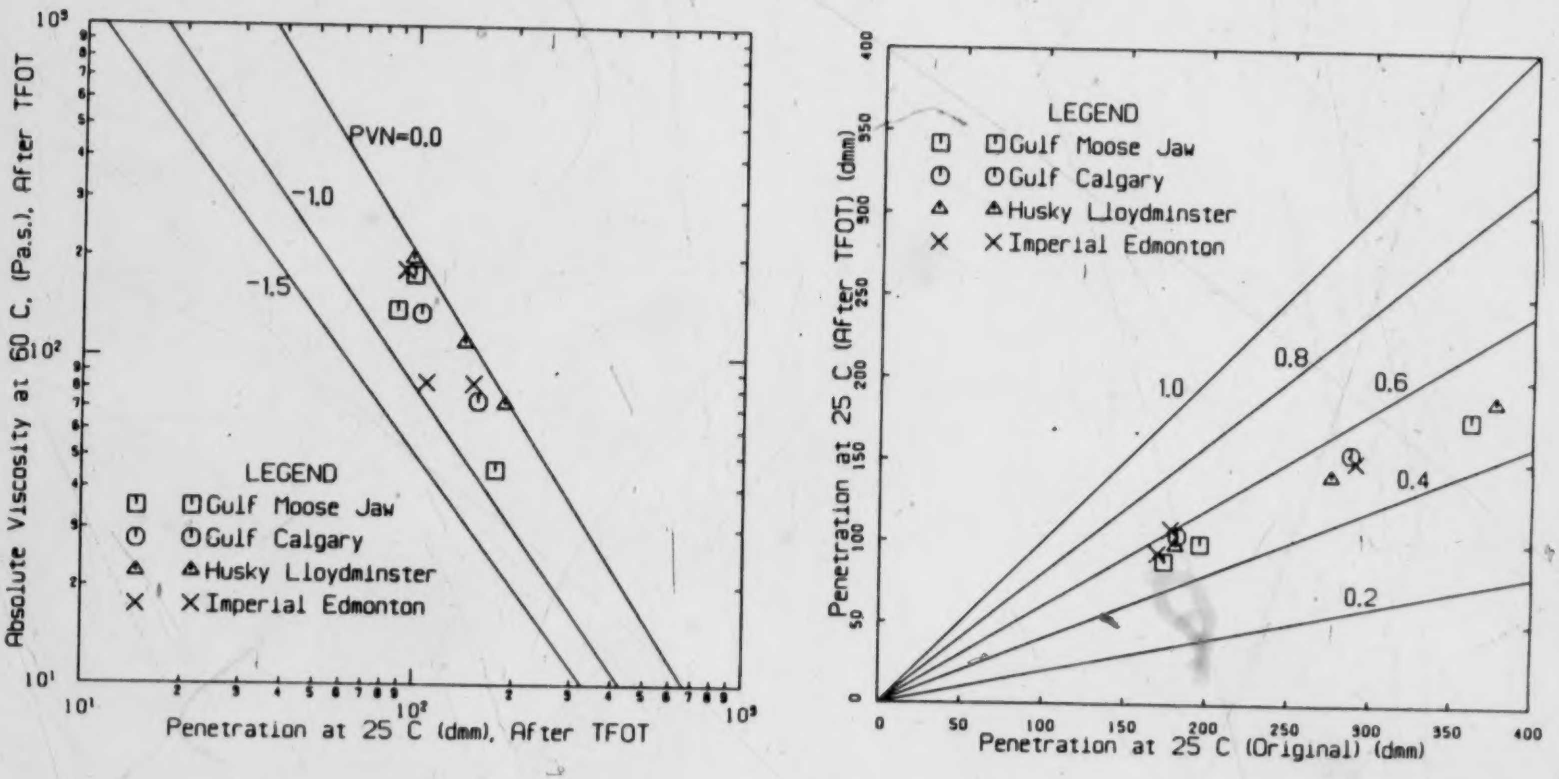
Figure 3.1 Comparison of Mean 1984 Asphalt Properties by Refineries



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

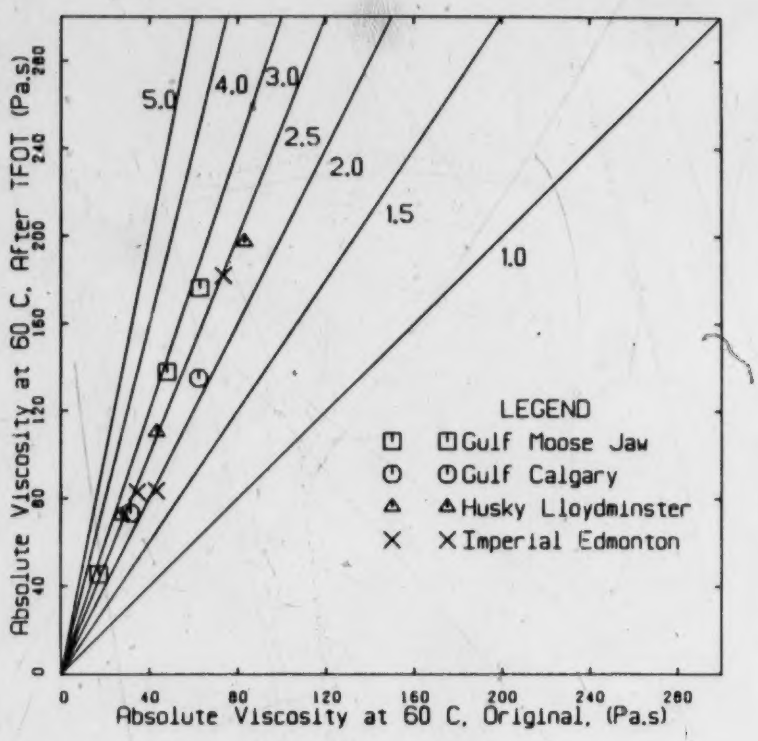
Figure 3.2 Comparison of Mean 1979 Asphalt Properties by Refineries



(c) TPen 25 C versus TVis 60 C

(d) Pen 25 C versus TPen 25 C

Figure 3.2 Comparison of Mean 1979 Asphalt Properties by Refineries



(e) Vis 60 C versus TVis 60 C

Figure 3.2 Comparison of Mean 1979 Asphalt Properties by Refineries

4. ASPHALT SPECIFICATION AND PROPERTIES

4.1 Grading of Asphalt Cement

There are many grading systems which are being used in North America. Different government agencies adopt different systems. However, the most widely used grading systems are based on: viscosity, viscosity after aging, penetration and a combination of the above.

In the U.S., the most widely used system is based on viscosity. (ASTM D3381, Table 4.1) In this system, the asphalt viscosity values at 60 C and 135 C, and penetration at 25 C are specified. Figure 4.1 and 4.2 show the requirements of the specification in a penetration-viscosity plot. The asphalt viscosity at 60 C represents the consistency of asphalt at the maximum temperature the pavement is likely to experience while in service, while the viscosity at 135 C approximates the consistency of asphalt during mixing and lay down. The penetration at 25 C represents the consistency of asphalt at average pavement service temperature. Knowing the consistency of a particular asphalt at these temperatures helps to determine whether the asphalt is suitable for the pavement being designed.

In several Western states, asphalt is graded according to their viscosities after aging. The idea is to identify the viscosity characteristics after it is placed in the pavement. To simulate aging in the asphalt plant during mixing, the asphalt is to be tested by a given standard aging exposure test in the laboratory. The asphalt residue that remains after aging is then graded according to its viscosity.

Grading asphalt according to the penetration at 25 C is an older method. However, it is still widely used. Table 4.2 shows the specification (ASTM D946) for penetration graded asphalt cement and Figure 4.3 represents the requirements graphically.

In Alberta, since 1980 asphalt cements have been graded by penetration at 25 C, plus additional viscosity requirements at 135 C and 60 C. The penetration at 25 C represents the consistency of asphalt cement at average pavement service temperature. Large penetration values indicate 'soft' asphalt whereas small penetration values indicate 'hard' asphalt. The viscosity requirement is intended to control the long term pavement performance, particular under low winter temperatures, by employing the penetration-viscosity relationship of asphalt cement. In other words, the temperature susceptibility of asphalt cement, which can be expressed as PVN or PI, is indirectly specified.

4.2 Historical Changes of Asphalt Specification in Alberta

The specification of asphalt cement being used in Alberta has been changed several times since the sixties (24). Prior to 1967, asphalt cements of penetration 120/150, 150/200 and 200/300 grade were specified with the

200/300 grade most commonly used. There was no viscosity requirement in the specification. In 1967, based on extensive surveys of crack occurrence of the main highway system and results of road tests, the Department of Highways (now Alberta Transportation) revised the specification and called for a minimum penetration of 250 at 25 C and a minimum absolute viscosity of 275 poise at 60 C for as supplied material. Figure 4.4a shows the historical requirements graphically and contains some of the test data of the asphalt cement used prior to and after the 1967 specification change. The additional minimum viscosity requirement had resulted in a more uniform product from various sources, eliminated the tenderness problem and reduced the incidence of low temperature cracking under normal winter conditions (24).

In 1978 and 1979, two new grades of asphalt cements were introduced. They were AC60 and AC27.5. Both grades were specified by penetration at 25 C as well as viscosity at 60 C. Figure 4.4b shows the requirements graphically. Other asphalt grades, though not specified in the 1978 and 1979 specification, were also used during this period. They were AC20.0, AC1.5 and 150/200.

In 1980, a new specification based on penetration and viscosity was introduced. (Table 4.3) It consists of three premium grades: 150/200A, 200/300A, and 300/400A; and two regular grades: 200/300B and 300/400B. Figure 4.5 shows the new specification graphically.

The numerical grade designation refers to minimum and maximum penetration and the letter suffix refers to premium or high viscosity (A) and regular or low viscosity (B). The specification is based on the rationale that temperature susceptibility is a major factor in selecting paving asphalts. The asphalt selected should be able to resist low temperature transverse pavement cracking at the minimum winter pavement temperature and at the same time should be able to provide adequate stability for heavy, medium or light traffic at the maximum summer temperature.

The premium grade, which has low temperature susceptibility and hence a better resistance to low temperature transverse cracking, is intended for use in regions with cold winter temperatures whereas the regular grade, which is more temperature susceptible, is intended for use in regions of milder winters, lighter summer traffic or confined to the lower pavement lifts. The harder grade asphalt, for example, pen 150/200, is intended for use in regions with high summer temperatures and/or heavy truck traffic, while the softer grade, for example, pen 300/400 , can be used in regions of cooler summers and lighter traffic.

4.3 Effect of the Change of Specification

In order to evaluate the effects of the changes of asphalt specification in 1980 to the properties of asphalts, the properties of the 1979 asphalts were compared with the

1984 asphalts for each refinery. (Table 4.4 to 4.6)

1. Most refineries in 1984, had produced asphalts of lesser temperature susceptibility than in 1979.

   The Gulf and Imperial test data show that the asphalts produced in 1984 are less temperature susceptible than those produced in 1979 as indicated by the temperature susceptibility parameters PVN(25-60) and PVN(25-135).

   The Husky test data show that there has been little change in temperature susceptibility of the asphalts produced since 1979.

2. There is generally a greater hardening and weight loss after the TFOT since the change of specification in 1979, even though the results are much within the specification limits.

   The retained penetration and viscosity ratio of the Gulf asphalts produced in 1979 and 1984 remain relatively unchanged. However, the percent weight loss of the 1984 product is substantially greater than that of the 1979 product. This indicated that the Gulf asphalts have become less durable since 1979.

   The Imperial asphalts have also become slightly less durable since 1979 as indicated by their increase in percent weight loss and viscosity ratio. The smaller retained penetration of the 1984 product also confirms the above observation. The durability of the Husky asphalts, on the contrary, have improved over the period from 1979 to 1984. The 1984 Husky asphalts have a slight increase in retained penetration and a decrease in viscosity ratio. Furthermore, their percent weight loss has reduced substantially since 1979.

3. The change of specification has also affected the variation of properties of asphalts produced since 1979. The Husky asphalts, particularly the 150/200 grade, have become more uniform in their consistency properties.

4.4 Summary

Table 4.7 shows the comparison of the properties of the 1979 and 1984 asphalts from all sources. Figure 4.6 presents the comparison of the 1979 and 1984 asphalt properties graphically.

From the table and figures, it is noted that the change in specification in 1980 has affected the properties of the asphalt cement being produced. The general effects are that the overall 1984 asphalt cements have become less temperature susceptible, slightly less durable and more uniform. The exception is the Husky asphalts which have shown improvement in resistance to TFOT aging and have remained relatively unchanged in temperature susceptibilty.

TABLE 1

NOTE—Grading based on original asphalt

Test	Viscosity Grade				
	AC-2.5	AC-5	AC-10	AC-20	AC-40
Viscosity, 140°F (60°C), P	250 ± 50	500 ± 100	1000 ± 200	2000 ± 400	4000 ± 800
Viscosity, 275°F (135°C), min, cSt	80	110	150	210	300
Penetration, 77°F (25°C), 100 g, 5 s, min	200	120	70	40	20
Flash point, Cleveland open cup, min, °F (°C)	325 (163)	350 (177)	425 (219)	450 (232)	450 (232)
Solubility in trichloroethylene, min, %	99.0	99.0	99.0	99.0	99.0
Tests on residue from thin-film oven test					
Viscosity, 140°F (60°C), max, P	1250	2500	5000	10,000	20,000
Ductility, 77°F (25°C), 5 cm/min, min, cm	100*	100	50	20	10

* If ductility is less than 100, material will be accepted if ductility at 60°F (15.5°C) is 100 minimum at a rate of 5 cm/min

TABLE 2

NOTE—Grading based on original asphalt

Test	Viscosity Grade				
	AC-2.5	AC-5	AC-10	AC-20	AC-40
Viscosity, 140°F (60°C), P	250 ± 50	500 ± 100	1000 ± 200	2000 ± 400	4000 ± 800
Viscosity, 275°F (135°C), min, cSt	125	175	250	300	400
Penetration, 77°F (25°C), 100 g, 5 s, min	220	140	80	60	40
Flash point, Cleveland open cup, min, °F (°C)	325 (163)	350 (177)	425 (219)	450 (232)	450 (232)
Solubility in trichloroethylene, min, %	99.0	99.0	99.0	99.0	99.0
Tests on residue from thin-film oven test					
Viscosity, 140°F (60°C), max, P	1250	2500	5000	10,000	20,000
Ductility 77°F (25°C), 5 cm/min, min, cm	100*	100	75	50	25

* If ductility is less than 100, material will be accepted if ductility at 60°F (15.5°C) is 100 minimum at a rate of 5 cm/min

Table 4.1 Requirements for Asphalt Cement, Viscosity Graded, Table 1&2, ASTM D3381

	Penetration Grade									
	40-50		60-70		85-100		120-150		200-300	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Penetration at 77°F (25°C) 100 g, 5 s	40	50	60	70		100		150	200	300
Flash point, °F (Cleveland open cup)	450	...	450	...		...		...	350	...
Ductility at 77°F (25°C) 5 cm/min, cm	100	...	100	...	100	...	100	...	100[A]	...
Retained penetration after thin-film oven test, %	55+	...	52+	...	47+	...	42+	...	37+	
Ductility at 77°F (25°C) 5 cm/min, cm after thin-film oven test	...	...	50	...	75	...	100	...	100[A]	...
Solubility in trichloroethylene, %	99.0	...	99.0		99.0	...	99.0		99.0	...

[A] If ductility at 77°F (25°C) is less than 100 cm, material will be accepted if ductility at 60°F (15.5°C) is 100 cm minimum at the pull rate of 5 cm/min

Table 4.2 Requirements for Asphalt Cement, Penetration Graded, ASTM D946

SPECIFICATIONS FOR ASPHALT CEMENTS: Asphalt cements shall conform to the requirements specified in the following table:

TEST CHARACTERISTICS	A.S.T.M. TEST METHODS	PREMIUM GRADES OF ASPHALT CEMENTS			REGULAR GRADES OF ASPHALT CEMENTS	
		150-200 (A)	200-300 (A)	300-400 (A)	200-300 (B)	300-400 (B)
Absolute Viscosity, 60°C, Pa·s Penetration, 25°C, 100 g, 5 s, dmm	D2171 D5	The viscosity and penetration values must fall within the area bounded by A - B - C - D - A, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Abs.Visc. Pen. A 155 150 B 70 150 C 50 200 D 92 200	The viscosity and penetration values must fall within the area bounded by C - D - E - F - C, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Abs.Visc. Pen. C 50 200 D 92 200 E 45 300 F 26.5 300	The viscosity and penetration values must fall within the area bounded by E - F - G - H - E, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Abs.Visc. Pen. E 45 300 F 26.5 300 G 17 400 H 27 400	The viscosity and penetration values must fall within the area bounded by C - J - K - F - C, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Abs.Visc. Pen. C 50 200 J 30 200 K 17.5 300 F 27 300	The viscosity and penetration values must fall within the area bounded by F - K - L - G - F, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Abs.Visc. Pen. F 26.5 300 K 17.5 300 L 12 400 G 17 400
Kinematic Viscosity, 135°C, mm²/s Penetration, 25°C, 100 g, 5s, dmm	D2170 D5	The viscosity and penetration values must fall within the area bounded by A - B - C - D - A, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Kin.Visc. Pen. A 360 150 B 255 150 C 205 200 D 265 200	The viscosity and penetration values must fall within the area bounded by C - D - E - F - C, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Kin.Visc. Pen. C 205 200 D 265 200 E 205 300 F 150 300	The viscosity and penetration values must fall within the area bounded by E - F - G - H - E, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Kin.Visc. Pen. E 205 300 F 150 300 G 120 400 H 165 400	The viscosity and penetration values must fall within the area bounded by C - J - K - F - C, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Kin.Visc. Pen. C 205 200 J 165 200 K 125 300 F 150 300	The viscosity and penetration values must fall within the area bounded by F - K - L - G - F, plotted as straight lines on a full logarithmic plot (log-log), with the co-ordinates of the points as follows: Pt. Kin.Visc. Pen. F 150 300 K 125 300 L 102.5 400 G 120 400
Flash Point, Cleveland Open Cup, °C minimum	D92	205	175	175	175	175
Solubility in Trichloroethylene, % minimum	D2042	99.5	99.5	99.5	99.5	99.5
Tests on Residue from Thin-Film Oven Test:	D1754					
Ratio of Absolute Viscosity of Residue from Thin-Film Oven Test to Original Absolute Viscosity, maximum	D2171	4.0	4.0	4.0	5.0	5.0
Ductility, 25°C, cm, minimum	D113	100	—	—	—	—
Ductility, 15.6°C, cm, minimum		—	100	100	100	100

General Requirement - The asphalt shall be prepared by the refining of petroleum. It shall be uniform in character and shall not foam when heated to 175°C.

- The temperature at delivery to the site shall be between 135°C and 175°C.

Table 4.3 1980 Alberta Transportation Specification for Asphalt Cement

Table 4.4 Comparison of Gulf 1979 and 1984 Asphalts

Properties	1984		1979			
	Moose Jaw		Moose Jaw		Calgary	
	150/200A	200/300A	150/200	AC 60.0	AC 60.0	AC 27.5
Pen 25 C (dmm)	208	244	174	196	182	288
(C. V. %)	(23)	(N.A.)	(6)	(N.A.)	(10)	(10)
Vis 60 C (Pa.s)	67.3	45.6	48.0	62.9	62.3	31.5
(C. V. %)	(22)	(N.A.)	(6)	(N.A.)	(11)	(7)
Vis 135 C (Cst.)	238	209	198	239	234	165
(C. V. %)	(11)	(N.A.)	(2)	(N.A.)	(10)	(5)
PVN(25-60)	-0.00	-0.10	-0.67	-0.14	-0.29	-0.26
PVN(25-135)	-0.18	-0.16	-0.70	-0.22	-0.36	-0.37
TFPVN(25-60)	-0.15	-0.42	-0.66	-0.18	-0.39	-0.39
% Wt. Loss	0.60	0.74	0.28	0.49	0.18	0.25
Vis Ratio	2.80	2.43	2.88	2.80	2.19	2.31
Retained Pen	0.50	0.48	0.50	0.51	0.58	0.56

Table 4.5 Comparison of Husky 1979 and 1984 Asphalts

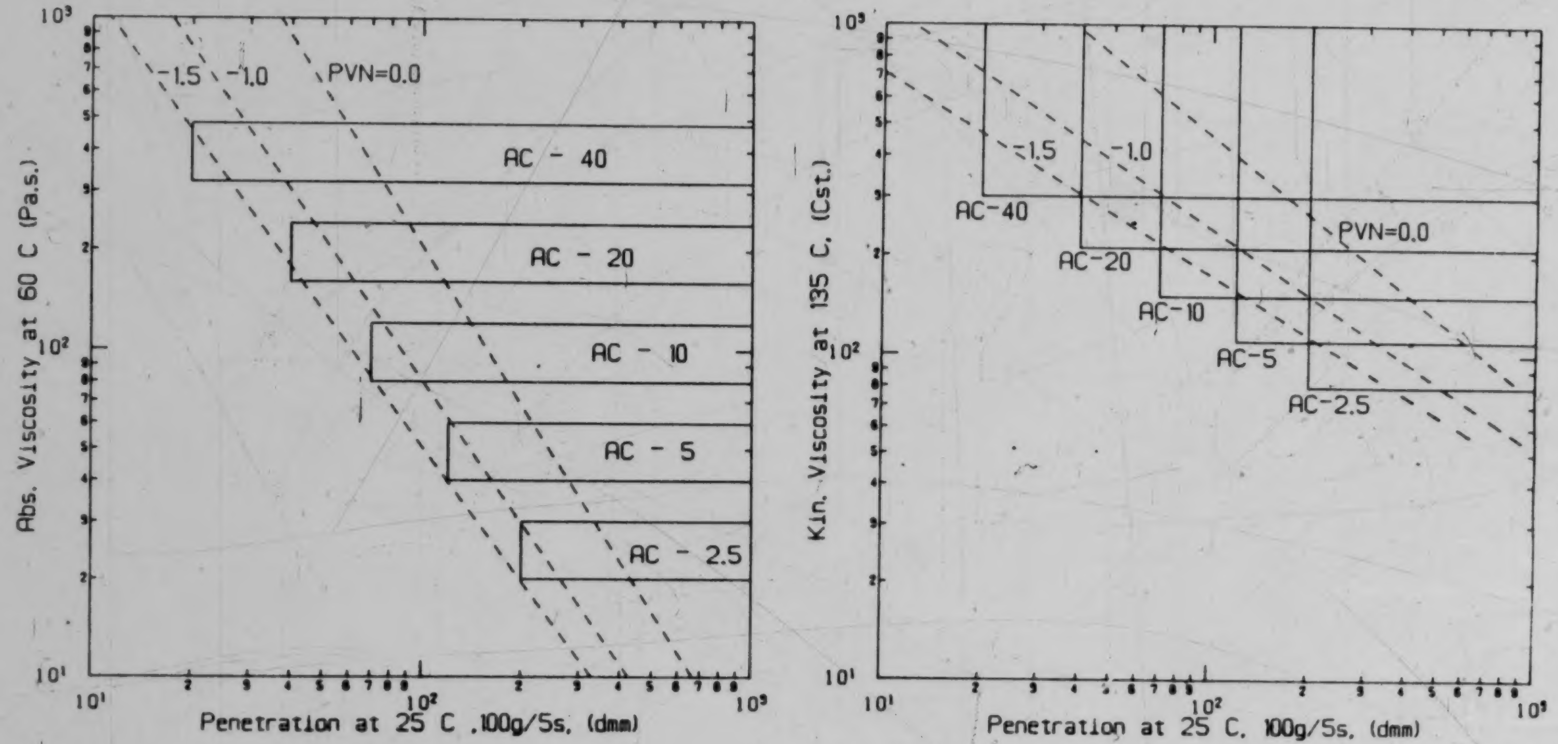
Properties	1984		1979	
	150/200A	200/300A	AC 60.0	AC 27.5
Pen 25 C (dmm)	169	276	181	276
(C. V. %)	(7)	(6)	(33)	(5)
Vis 60 C (Pa.s)	81.5	42.6	83.0	43.3
(C. V. %)	(8)	(7)	(19)	(7)
Vis 135 C (Cst.)	273	201	267	200
(C. V. %)	(5)	(6)	(17)	(4)
PVN(25-60)	-0.11	+0.05	-0.04	+0.08
PVN(25-135)	-0.19	-0.05	-0.20	-0.05
TFPVN(25-60)	-0.14	-0.07	-0.11	-0.08
% Wt. Loss	0.31	0.61	0.55	0.86
Vis Ratio	2.30	2.46	2.41	2.55
Retained Pen	0.58	0.53	0.56	0.51

Table 4.6 Comparison of Imperial 1979 and 1984 Asphalts

Properties	1984		1979		
	150/200A	200/300A	150/200	AC 60.0	AC 27.5
Pen 25 C (dmm) (C. V. %)	160 (7)	234 (7)	178 (15)	170 (5)	291 (8)
Vis 60 C (Pa.s) (C. V. %)	80.0 (10)	44.6 (13)	43.2 (15)	73.4 (6)	34.5 (10)
Vis 135 C (Cst.) (C. V. %)	259 (7)	189 (8)	200 (9)	247 (5)	174 (8)
PVN(25-60)	-0.23	-0.22	-0.78	-0.21	-0.12
PVN(25-135)	-0.35	-0.31	-0.68	-0.35	-0.25
TFPVN(25-60)	-0.24	-0.37	-0.88	-0.25	-0.31
% Wt. Loss	0.55	0.71	0.09	0.38	0.63
Vis Ratio	2.76	2.65	1.91	2.49	2.41
Retained Pen	0.51	0.49	0.62	0.55	0.52

Table 4.7 Comparison of 1979 and 1984 Asphalts from All Sources

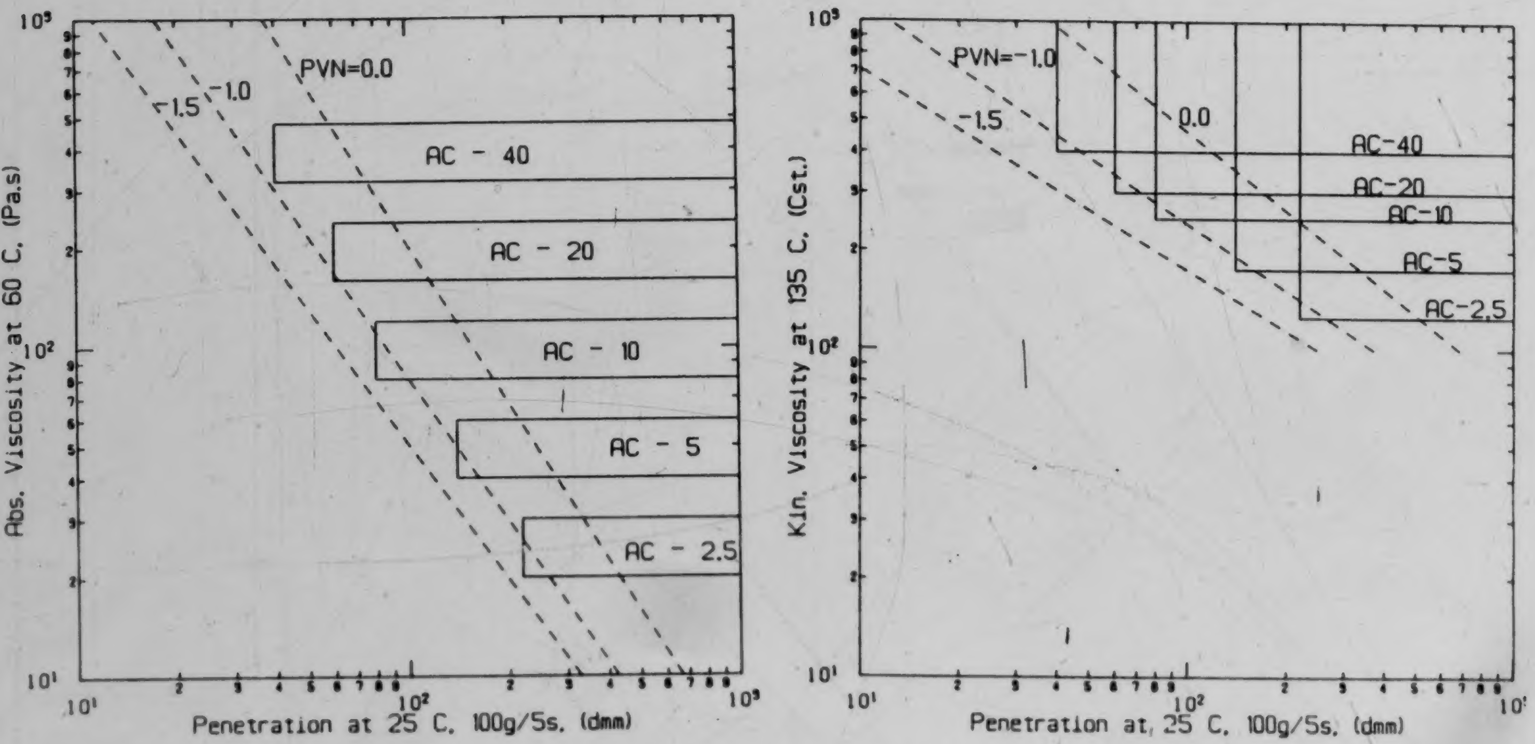
	1984		1979		
	150/200A	200/300A	150/200	AC 60.0	AC 27.5
Pen 25 C (dmm) (C. V. %)	167 (10)	251 (10)	176 (13)	176 (15)	286 (7)
Vis 60 C (Pa.s) (C. V. %)	80.4 (10)	43.8 (11)	45.0 (13)	71.8 (14)	37.4 (14)
Vis 135 C (Cst.) (C. V. %)	266 (7)	200 (7)	199 (7)	247 (10)	183 (9)
PVN(25-60)	-0.15	-0.11	-0.74	-0.20	-0.12
PVN(25-135)	-0.26	-0.21	-0.68	-0.33	-0.25
TFPVN(25-60)	-0.19	-0.24	-0.80	-0.26	-0.31
% Wt. Loss	0.43	0.67	0.16	0.36	0.70
Vis Ratio	2.53	2.57	2.27	2.41	2.41
Retained Pen	0.55	0.51	0.57	0.56	0.52



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

Figure 4.1 Specification for Viscosity Graded Asphalt (Table 1, ASTM D3381)



(a) Pen 25 C versus Vis 60 C

(b)Pen 25 C versus Vis 135 C

Figure 4.2 Specification for Viscosity Graded Asphalt (Table 2, ASTM D3381)

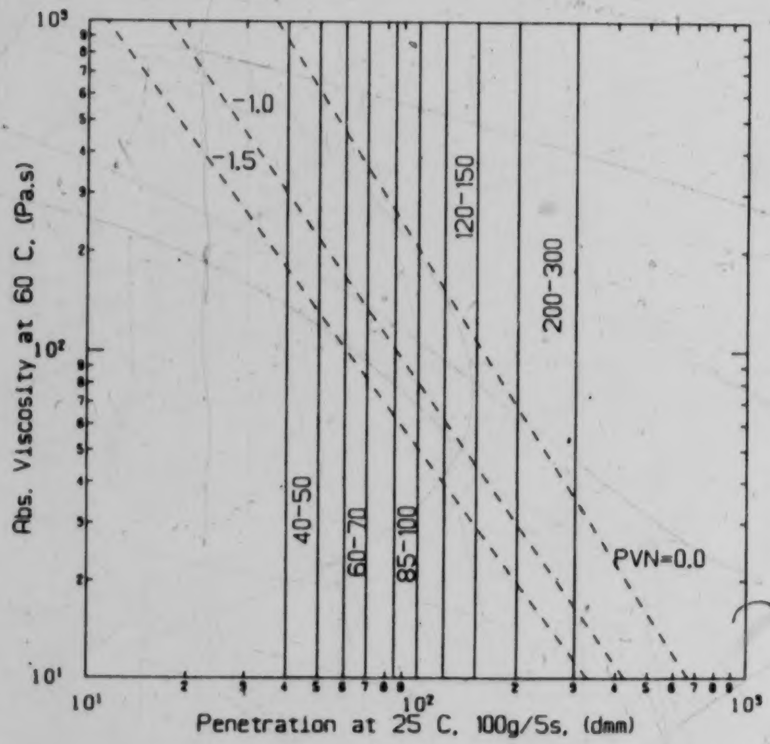
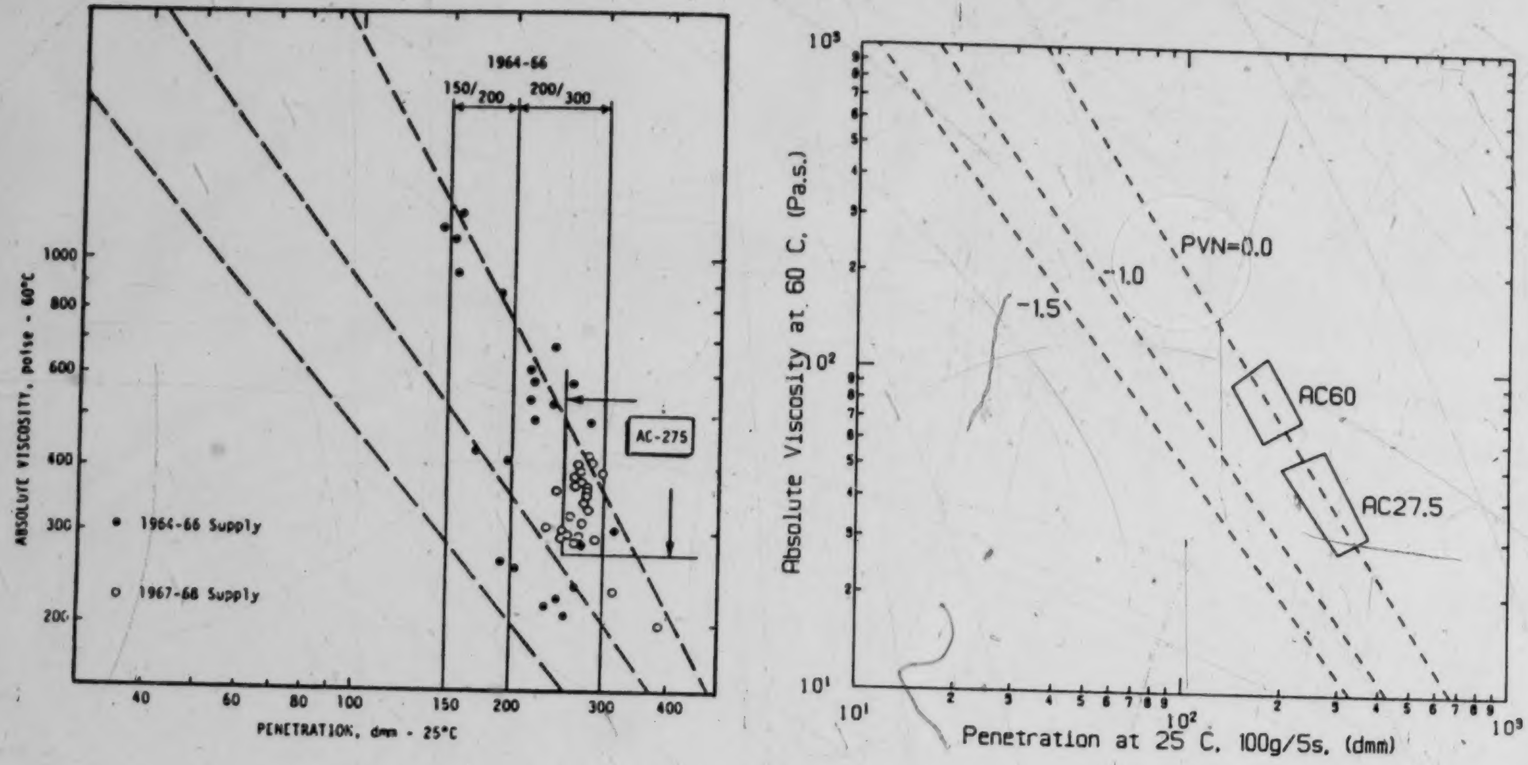


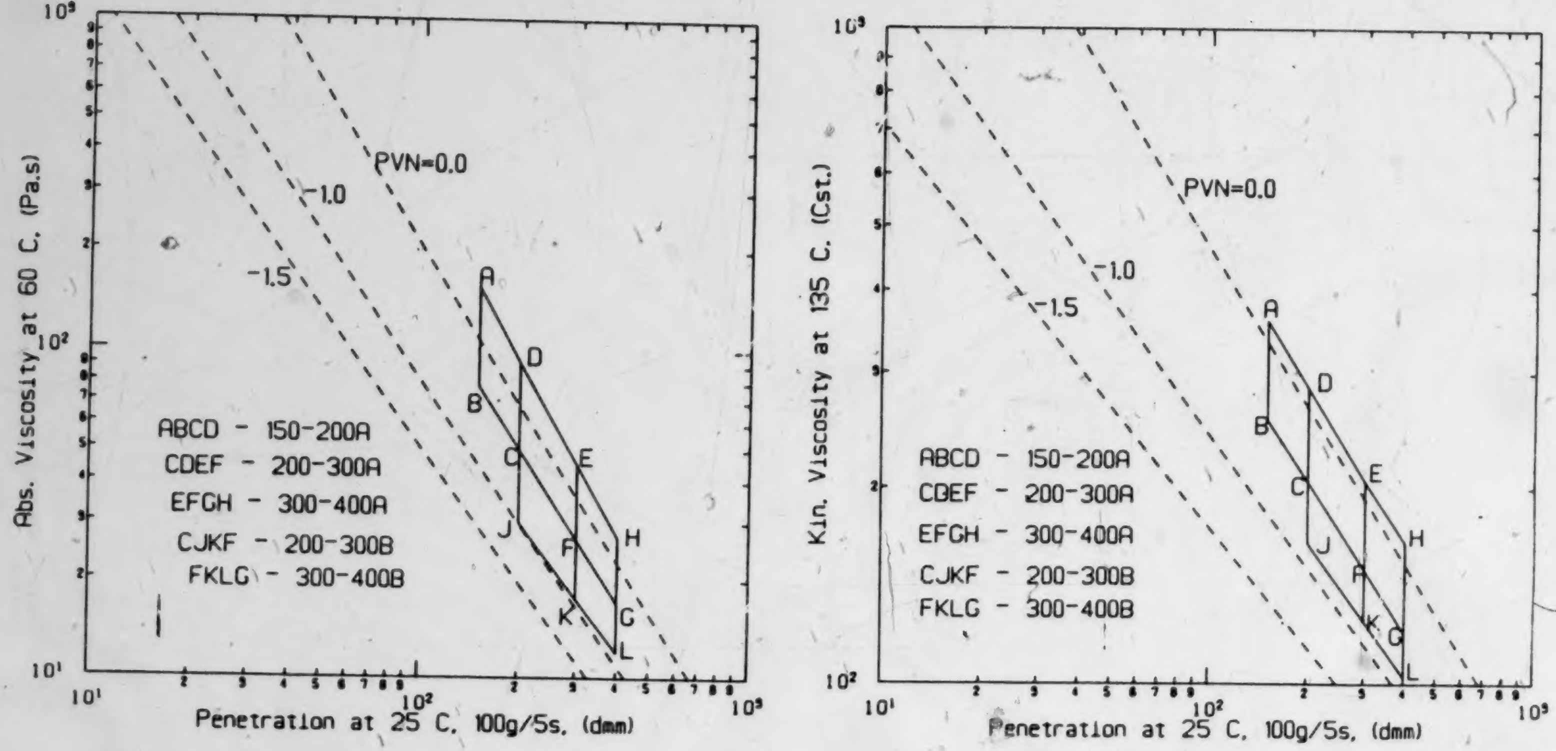
Figure 4.3 Specification for Penetration Graded Asphalt (Table 1, ASTM D946)



a) 1964-1968

b) 1978-1979

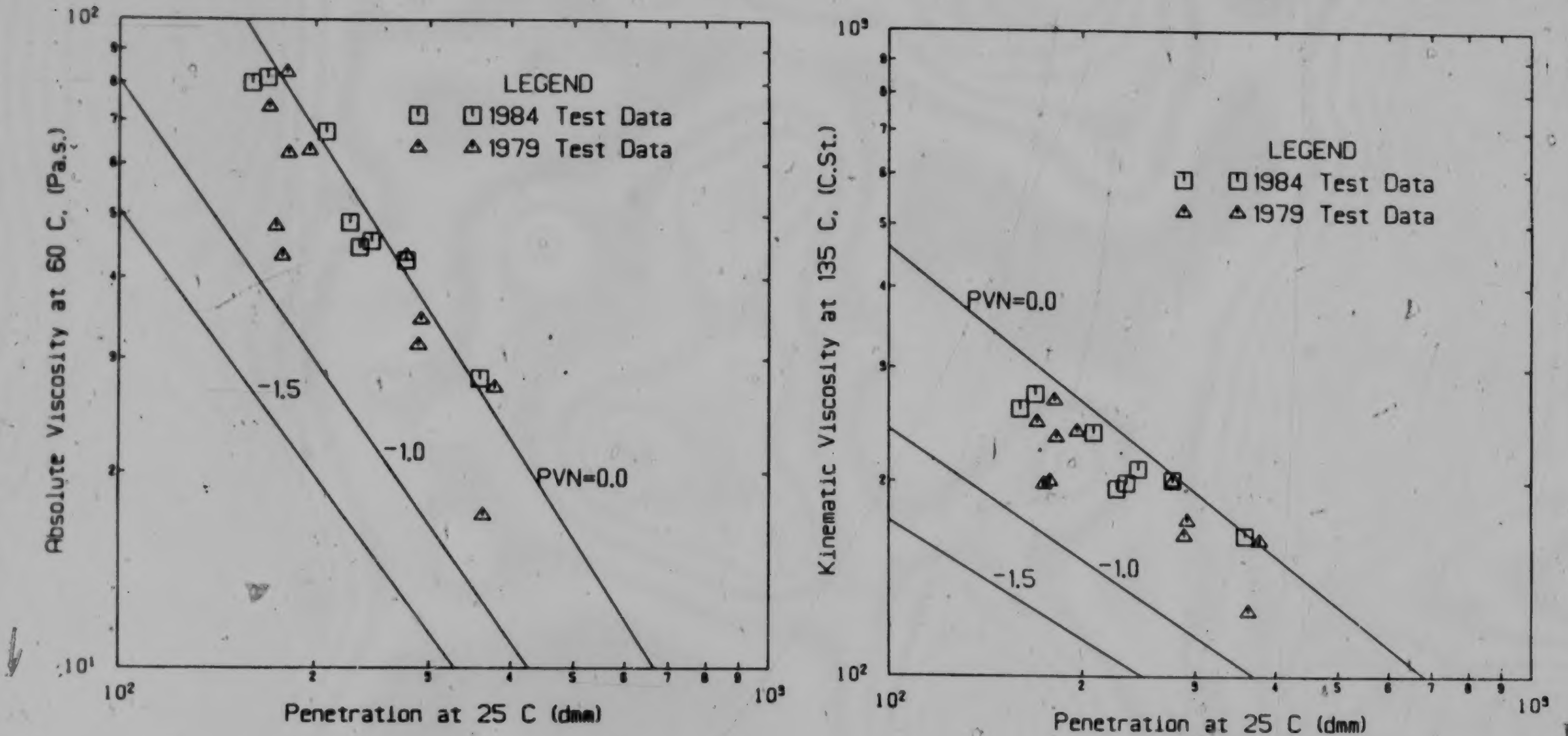
Figure 4.4 Alberta Specification for Penetration Graded and Pen/Vis Graded Asphalt, 1964-1978



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

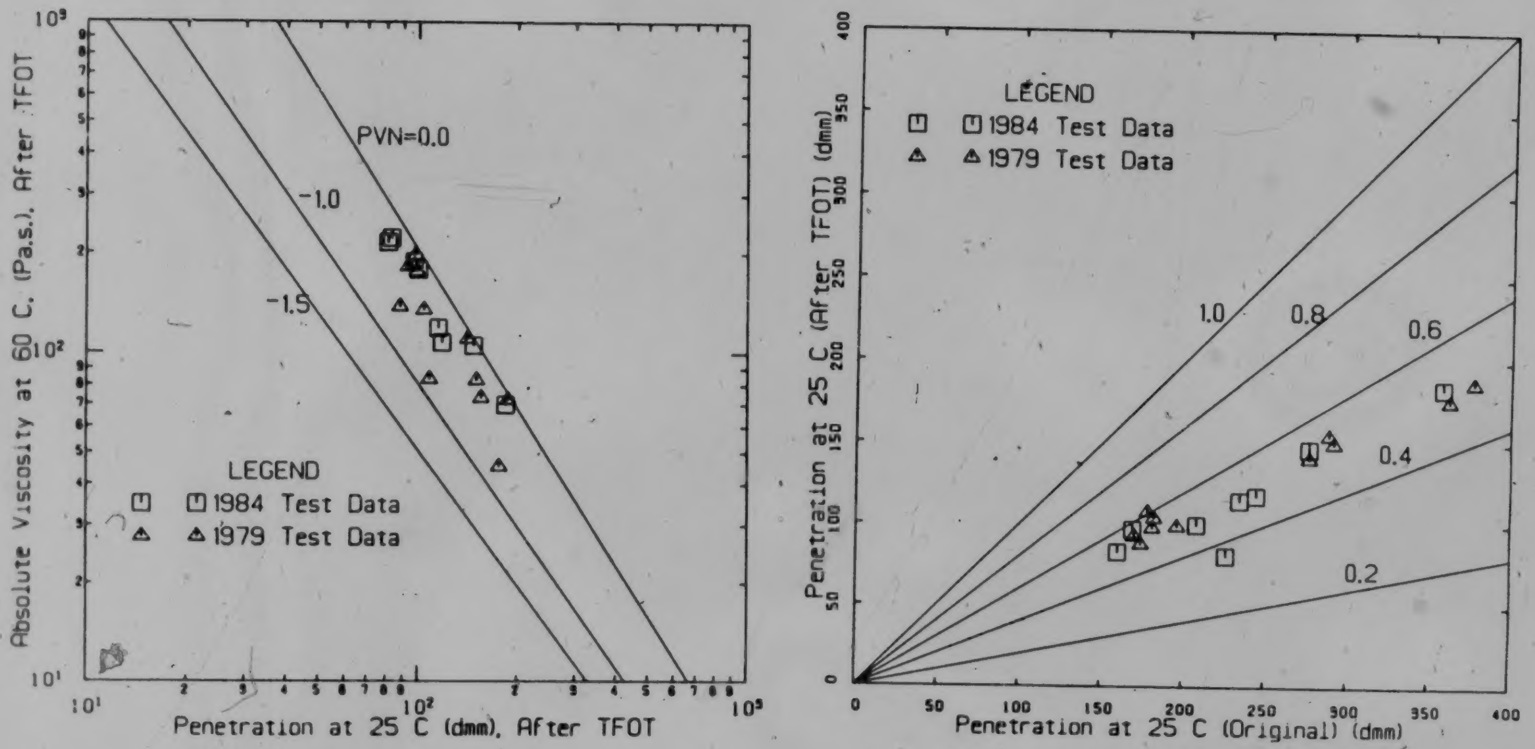
Figure 4.5 Alberta Specification for Pen/Vis Graded Asphalts, 1980



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

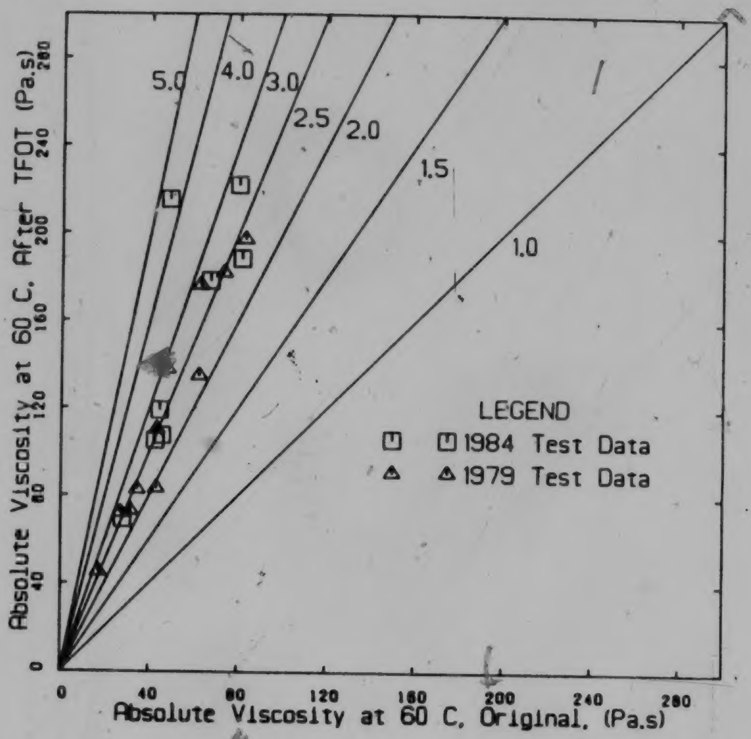
Figure 4.6 Comparison of the Mean 1984 and 1979 Asphalt Properties



(c) TPen 25 C versus TVis 60 C

(d) Pen 25 C versus TPen 25 C

Figure 4.6 Comparison of the Mean 1984 and 1979 Asphalt Properties



(e) Vis 60 C versus TVis 60 C

Figure 4.6 Comparison of the Mean 1984 and 1979 Asphalt Properties

5. LABORATORY TESTS OF ASPHALTS

5.1 Laboratory Testing Program

Following the analysis of historical test data, a laboratory testing program of selected asphalt cements was developed. The major objective of this testing program was to evaluate the low temperature performance of asphalt cements produced from different locally available crude sources.

Two grades of asphalt cement samples from different crude sources, representing asphalt cements of different temperature susceptibilities were obtained from Esso Petroleum Canada and Husky Oil of Lloydminster.

Two types of laboratory tests were carried out. Conventional physical tests were carried out to define the rheological properties and temperature susceptibility parameters which were used in evaluating the low temperature performance of the selected asphalt cements.

The tensile splitting test, which has been used at the University of Alberta and improved in this project, was utilized in testing asphaltic concrete cylinders prepared from the different asphalt cements. The tensile properties obtained from the tests were used in evaluating the asphalt cements for low temperature performance.

5.2 Description of Asphalt Cement Samples

Two criteria were used for the selection of asphalt cements for laboratory testing. First, the selected samples were to represent a hard grade asphalt cement, (85/100) and a soft grade asphalt cement (200/300).

Secondly, the selected samples within a given grade were to represent different temperature susceptibility. In this regard, asphalt cements manufactured from different sources of crude oils were chosen. This included the Cold Lake asphalt cement and the Redwater-Gulf Blend asphalt cement, which were obtained from Esso Petroleum Canada. The Cold Lake asphalt cement, which was produced from heavy crude oils, was considered as low temperature susceptibility. The Redwater-Gulf Blend asphalt cement, which was specially formulated from lighter crude oils to exhibit high temperature susceptibility, was also chosen in order to render the greatest possible difference in temperature susceptibility between samples.

For comparison purpose, the asphalt cement produced from the heavy crude oils of the Lloydminster area was also obtained from Husky Oil of Lloydminster. This asphalt cement was considered as low temperature susceptibility.

As a result, a total of six asphalt cement samples was chosen for testing in the following laboratory tests.

5.3 Conventional Physical Tests

In this laboratory testing program, only the common physical tests of asphalt cements were carried out on the six samples. The primary emphasis was placed on the evaluation of the consistency properties of the materials, such as viscosity, penetration and ductility; and the temperature susceptibility parameters of the materials, such as Penetration Viscosity Numbers and Penetration Index.

Standard ASTM testing procedures were ultilized for all the physical tests. The major deviation in consistency tests from the standard testing procedures involved measurement of penetration at 4 C. In this case, only the temperature of the bath used for conditioning of the asphalt cements was adjusted. All the other testing conditions remained the same as described in the original standard tests. Thus, the penetration tests at 25 C and 4 C were made following ASTM D-5 procedures, by loading the needle with 100 grams for 5 seconds.

Similarly, in viscosity tests at 135 C and 60 C, the ASTM D2170 and ASTM D2171 standard test procedures were followed.

5.4 Presentation and Discussion of Test Results

5.4.1 Physical Properties

Table 5.1 summarizes the results of the physical tests that have been carried out in this phase of research.

Reported values are averages of five individual tests, except for softening point and ductility. Figure 5.1 and 5.2 show the absolute viscosity at 60 C and kinematic viscosity at 135 C plotted against penetration at 25 C. Appendix C gives the physical test data provided by the suppliers.

From the table, it is noted that the penetration at 25 C of the asphalts from all sources are quite uniform. However, the penetration at 4 C differs substantially between sources of the same grade. Particularly, the Redwater-Gulf Blend asphalt has the lowest penetration value at 4 C among the three asphalts of each grade. This indicates that this asphalt is harder than the Cold Lake and Lloydminster asphalts at low temperature even though they have similar penetration values at 25 C.

The viscosities (both at 135 C and 60 C) of the Redwater-Gulf Blend asphalt are particularly low (for both grades) when compared with the viscosities of the asphalts from Cold Lake and Lloydminster. This shows that the Redwater-Gulf Blend asphalt is a low viscosity asphalt.

The consistency measurements of the Cold Lake and Lloydminster asphalts are similar in most aspects.

The Redwater-Gulf Blend asphalt has the highest ring and ball softening point among the three asphalts, particularly in the 200/300 grade.

The ductility of all the asphalts meets the specification requirement of a minimum extension of 150 cm at 25 C .

5.4.2 Temperature Susceptibility Parameters

Table 5.2 presents the temperature susceptibility parameters, PVN(25-60), PVN(25-135), PI(R&B) and PI(dPen/dT), using data from Table 5.1 and equations described in Chapter II. Table 5.3 lists in decreasing order the temperature susceptibility of the asphalts by the four methods.

The Redwater-Gulf Blend asphalt is the most temperature susceptible in both grades according to the PVN and PI(dPen/dT) methods. On the contrary, the PI(R&B) method shows that this asphalt is the least temperature susceptible. Obviously, this is not correct because, as will be shown in the next section, the Redwater-Gulf Blend asphalt is a waxy asphalt which gives false R&B softening point leading to erroneous PI(R&B) values.

The temperature susceptibility of the Cold Lake and Lloydminster asphalts are very similar and the different temperature susceptibility parameters do not distinguish the order of their temperature susceptibility.

For the 85/100 grade asphalt samples, PVN values indicate that the Cold Lake asphalt is slightly more temperature susceptible than the Lloydminster asphalt with a maximum numerical difference of PVN values of 0.20. However, both the PI(dPen/dT) and PI(R&B) values indicate to the contrary. They indicate that the Lloydminster asphalt is more temperature susceptible as shown by the lower PI values. The maximum numerical differences are 0.65 and 0.19

respectively.

For the 200/300 grade asphalt samples, PVN values indicate that the temperature susceptibility of both the Lloydminster and Cold Lake asphalt are very similar with a maximum numerical difference of only 0.09. However, the PI(dPen/dT) values indicate that the Cold Lake asphalt is more temperature susceptible than the Lloydminster asphalt whereas the PI(R&B) indicate to the contrary. The PI(dPen/dT) of the Cold Lake sample is 0.83 more negative than the value of the Lloydminster sample whereas the PI(R&B) of the Lloydminster sample is 0.20 more.

The PVN(25-60) and PVN(25-135) values are quite similar with the PVN(25-135) generally having a slightly lower value. The maximum numerical difference is 0.28.

The PI and the PVN values are not equal. The PI(dPen/dT) values of all the test samples are substantially lower than the corresponding PVN(25-60) and PVN(25-135) values. The maximum numerical difference is as much as 1.88. The difference is obvious, since the PI(dPen/dT) employs two penetration readings which account for the temperature susceptibility of the lower temperature region; whereas the PVN employs one penetration and one viscosity reading which account for the temperature susceptibility of a wider and higher temperature region. The lower PI(dPen/dT) value shows that the temperature susceptibility of these asphalts are greater at low temperature than at high temperature.

The difference of temperature susceptibility between low and high temperature region is best illustrated by the Bitumen Test Data Chart which is the topic of the next section.

5.4.3 Bitumen Test Data Chart

Figure 5.3 to 5.5 show the plot of viscosities and penetration values of the six samples on the Bitumen Test Data Chart (BTDC) developed by Heukelom (10). The chart provides a convenient method to graphically present basic asphalt properties. The straight lines joining the viscosity data and the penetration data indicate the degree of temperature susceptibility in two temperature range. Steeper slopes indicate a greater temperature susceptibility.

From the BTDC, it is noted that the slopes of the straight lines joining the Redwater-Gulf Blend asphalt data are the steepest indicating that this asphalt is the most temperature susceptible among the three asphalts. The slope of the straight lines joining the Cold Lake and Lloydminster asphalts data are similar indicating that they have similar temperature susceptibilty.

It is also noted that the lines in the penetration region are all steeper than the lines in the viscosity region. This agrees with that the PI(dPen/dT) values are more negative than the PVN values as discussed before.

For the Cold Lake and Lloydminster asphalts, the straight lines joining the two viscosity values meet closely to the ring and ball softening points whereas the ring and ball softening point of the Redwater asphalts fall on the right hand side of the line. This is an indication that there may be wax presence in the Redwater-Gulf Blend asphalt. If wax is presence in the Redwater-Gulf Blend asphalt, the ring and ball softening point of this asphalt will be false and the PI(R&B) calculated for this asphalt will be an erroneous indicator of temperature susceptibility.

The uppermost intercept (where penetration is equal to one) in the penetration portion of the plot is an indicator of low temperature performance; poorer low temperature performance will be expected when these intercepts occur at higher temperatures. By comparing Figure 5.3 to 5.5, using the above method, it is noted that the Redwater-Gulf Blend asphalts have the highest temperature intercepts for both grades, indicating that they will have poorer performance at low temperature.

5.4.4 Stiffness Modulus

The tendency of a mix to crack at low temperature is related to the binder stiffness mudulus at low temperature and long loading time. In order to predict the low temperature cracking performance of the samples, the stiffness modulus of all the six samples have been determined at -30 C and -20 C using:

1. Original van der Poel Method

2. Heukelom's Modification Method and
3. McLeod's Method

The details of these methods have been described in Chapter 2.

A loading time of 20,000 seconds and 1800 seconds have been used and the calculated stiffness modulii are given in Table 5.4.

The stiffness modulii as calculated by the Heukelom and McLeod methods show that the Redwater-Gulf Blend asphalt has the highest stiffness among the three asphalts, at temperatures of -20 C and -30 C for loading times of 1800 seconds and 20,000 seconds. This indicates that this asphalt has the least resistance to low temperature cracking.

On the contrary, the stiffness modulii as calculated by the van der Poel's method show that the Redwater-Gulf Blend asphalt has the lowest stiffness among the three asphalts. Again, the erroneous indication is due to the use of the false ring and ball softening point in calculating the stiffness in the van der Poel's method.

The stiffness modulii of the Cold Lake and Lloydminster asphalts, as calculated by the three methods, are very close. Hence, the performance of these two asphalts at low temperatures is expected to be similar.

The stiffness modulii of the 85/100 grade asphalts are higher than the corresponding 200/300 grade asphalts when comparing asphalts of the same crude source. This is obvious since the harder grade asphalt is expected to be stiffer. However, the above logic may not hold when comparing asphalts from different crude sources. For example, the stiffness of the Redwater-Gulf Blend 200/300 grade asphalt, at -30 C and at both 1800 seconds and 20,000 seconds loading time is higher or equivalent to the Cold Lake and Lloydminster 85/100 grade asphalts. This clearly demonstrates that selecting softer grade asphalts to improve low temperature performance of asphalt pavement does not always work and that a hard grade asphalt may perform better than a soft grade asphalt depending on their temperature susceptibility.

5.4.5 Cracking Temperature

Cracking temperature of asphalt, as discussed in Chapter 2, is a more direct indication of the pavement's relative performance at low temperature. In this research, the cracking temperature of each asphalt sample has been calculated using Heukelom's modified method and based on a limiting asphalt stiffness of 1 X 10^9 N/m^2 at 1800 seconds loading time. The results of the calculation are tabulated in Table 5.5.

From the table, it is noted that for both grades the Redwater-Gulf Blend asphalts develop thermal cracking at a higher temperature than those of Cold Lake and Lloydminster. For the 85/100 grade asphalts, the differences in cracking temperatures among the three asphalts are not significant.

The Cold Lake asphalts have slightly lower cracking temperatures than the Lloydminster asphalts. For the 200/300 grade asphalts, the differences in cracking temperatures among the three asphalts are substantial. The Lloydminster asphalts have much lower cracking temperatures than the Cold Lake asphalts.

The softer asphalt (200/300) has a lower cracking temperature than the harder asphalt (85/100). The difference in cracking temperature between the two grades is significantly larger for the Lloydminster asphalts.

The calculated cracking temperatures may not be the actual cracking temperature of the pavement because of the assumption of a limiting stiffness of 1×10^9 N/m^2 at 1800 seconds loading time. However, the cracking temperatures computed have been shown to be excellent indicators for comparing the low temperature performance of various asphalts (15).

Table 5.1 Properties of Asphalt Samples

Properties	85/100			200/300		
	C. L.[1]	Lloyd.[2]	R. W.[3]	C. L.	Lloyd.	R. W.
Pen 25 C (dmm)	95	94	93	263	254	242
Pen 4 C (dmm)	9.0	6.8	5.7	19.3	26	10.3
Vis 60 C (Pa.s)	158.2	189.0	52.9	43.4	44.8	19.5
Vis 135 C (Cst.)	340	391	169	187	202	104
R&B S. P. (C)	45.0	44.5	47.0	36.0	36.0	42.0
Ductility (cm)	+150	+150	+150	+150	+150	+150

[1] Cold Lake
[2] Lloydminster
[3] Redwater-Gulf Blend

Table 5.2 Temperature Susceptibility Parameters

Parameters	85/100			200/300		
	C. L.	Lloyd.	R. W.	C. L.	Lloyd.	R. W.
PI(dPen/dT)	-1.27	-1.93	-2.28	-1.89	-1.06	-2.96
PI(R&B)	-0.95	-1.14	-0.40	-0.61	-0.81	+1.87
PVN(25-60)	-0.36	-0.19	-1.56	-0.01	-0.04	-1.18
PVN(25-135)	-0.53	-0.33	-1.61	-0.25	-0.16	-1.46

Table 5.3 Decreasing Order of Temperature Susceptibility

Grade	PI(dPen/dT)	PI(R&B)	PVN(25-60)	PVN(25-135)
Pen 85/100	R. W. Lloyd. C. L.	Lloyd.* C. L.* R. W.	R. W. C. L.* Lloyd.*	R. W. C. L.* Lloyd.*
Pen 200/300	R. W. C. L. Lloyd.	Lloyd.* C. L.* R. W.	R. W. Lloyd.* C. L.*	R. W. C. L.* Lloyd.*

*Values are close

Table 5.4 Stiffness Modulus* of Asphalt Samples

	85/100			200/300		
	C. L.[1]	Lloyd.[2]	R. W.[3]	C. L.	Lloyd.	R. W.
(1) Loading Time = 20,000 Seconds						
(a) At -30 C						
(i) van der Poel	50.0	50.0	22.0	3.0	3.0	0.7
(ii) Heukelom	50.0	100.0	150.0	10.0	5.0	50.0
(iii) McLeod	20.0	20.0	100.0	1.5	2.0	10.0
(b) At -20 C						
(i) van der Poel	3.0	5.0	3.0	0.2	0.2	0.1
(ii) Heukelom	5.0	5.0	8.0	0.4	0.2	1.0
(iii) McLeod	2.0	2.0	10.0	0.1	0.2	0.5
(2) Loading Time = 1800 Seconds						
(a) At -30 C						
(i) van der Poel	100.0	150.0	90.0	15.0	20.0	2.0
(ii) Heukelom	200.0	500.0	800.0	50.0	20.0	500.0
(iii) McLeod	100.0	80.0	500.0	8.0	10.0	80.0
(b)At -20 C						
(i) van der Poel	20.0	25.0	15.0	1.5	1.5	0.4
(ii) Heukelom	30.0	40.0	50.0	4.0	1.5	10.0
(iii) McLeod	10.0	10.0	90.0	0.8	1.0	4.0

*Unit of Stiffness Modulus is in MPa

[1] Cold Lake

[2] Lloydminster

[3] Redwater-Gulf Blend

Table 5.5 Estimated Cracking Temperature* of Asphalt Samples

	85/100			200/300		
	C. L.	Lloyd.	R. W.	C. L.	Lloyd.	R. W.
PI(dPen/dT)	-1.27	-1.93	-2.28	-1.89	-1.06	-2.96
T(diff)	86.0	77.0	73.0	78.0	90.0	64.0
T(800 pen)	44.5	41.0	40.0	33.5	34.5	32.0
Crack Temp.(C)	-41.5	-36.0	-33.0	-44.5	-55.5	-32.0

*Assuming limiting stiffness equals to 1 X 10^9 N/m^2 at 1800 seconds loading time

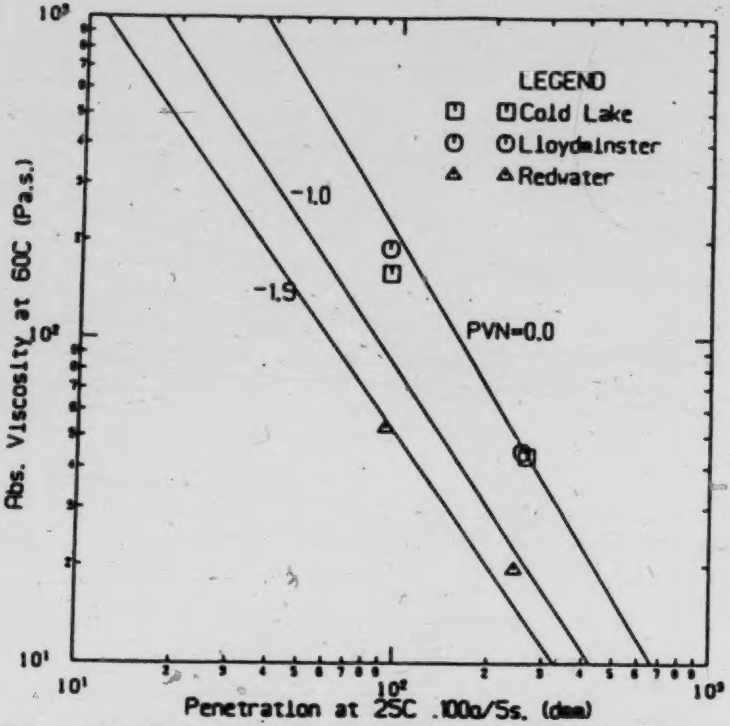


Figure 5.1 Pen 25 C - Vis 60 C Relationships of Asphalt Samples

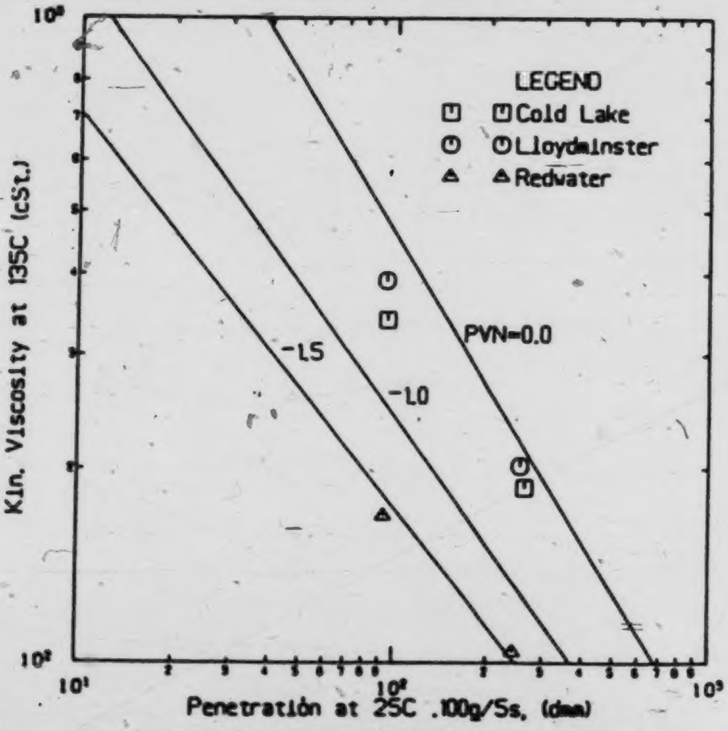
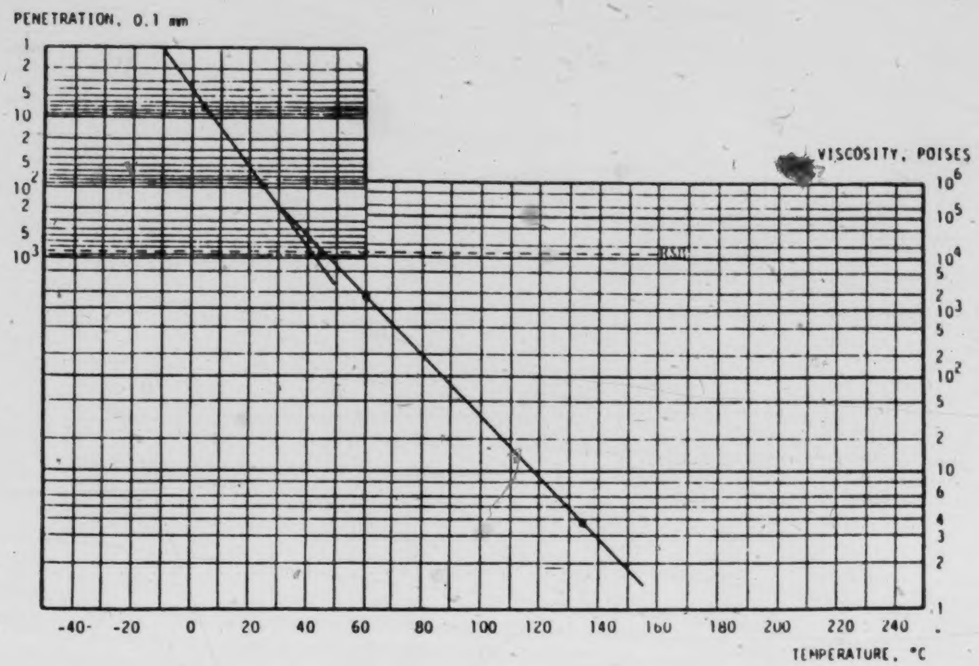
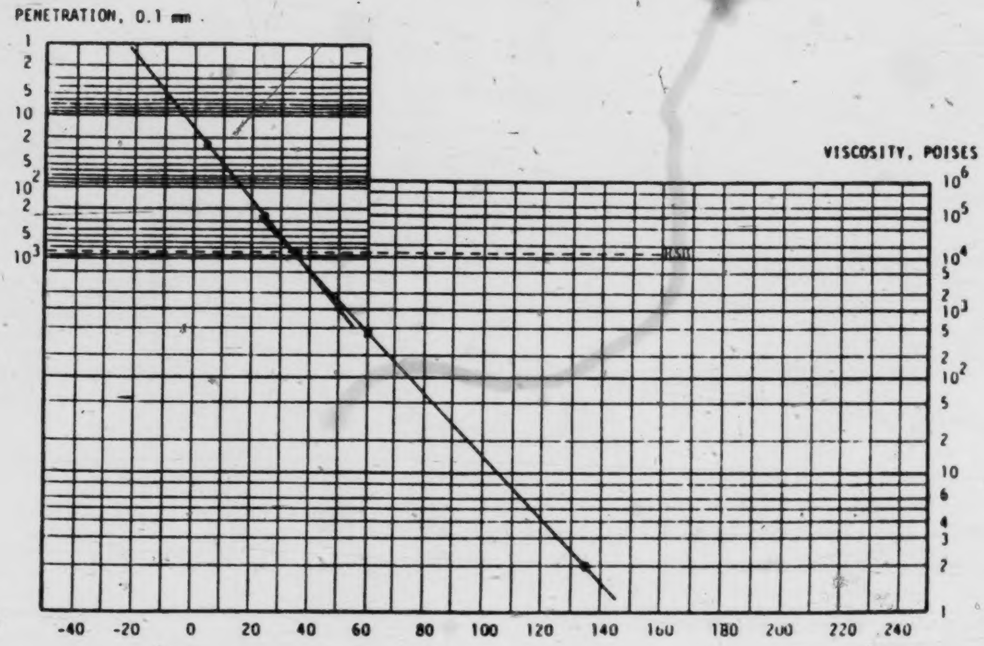


Figure 5.2 Pen 25 C - Vis 135 C Relationships of Asphalt Samples

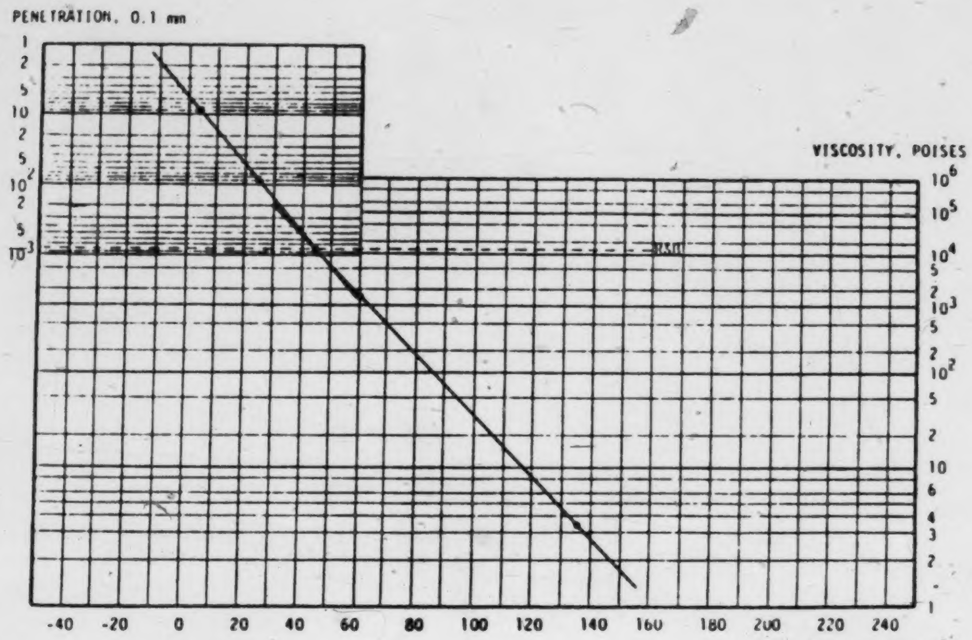


(a) Pen 85/100

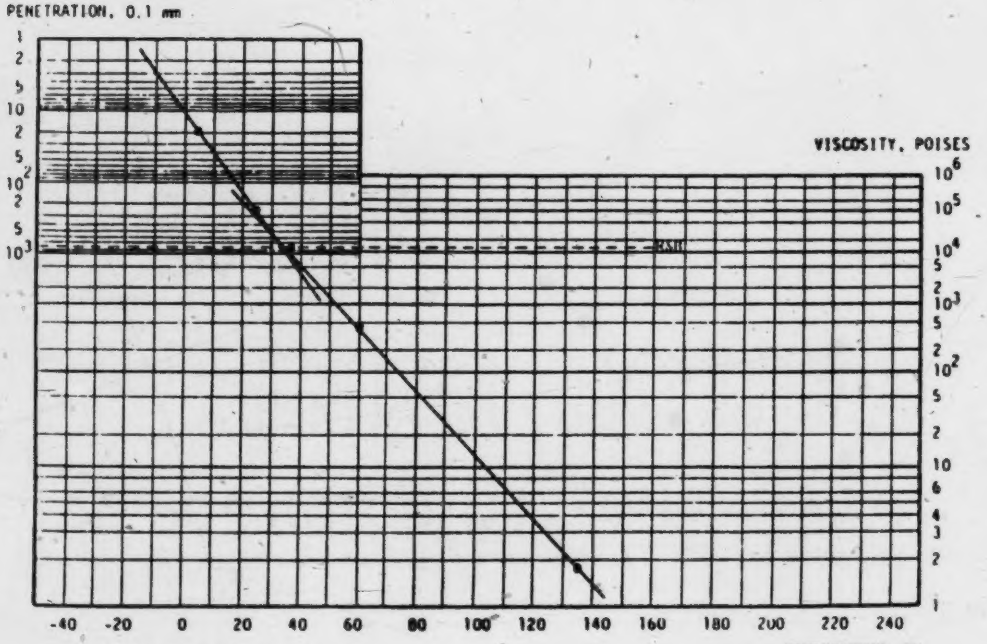


(b) Pen 200/300

Figure 5.3 Bitumen Test Data Charts showing Test Results of Lloydminster Samples

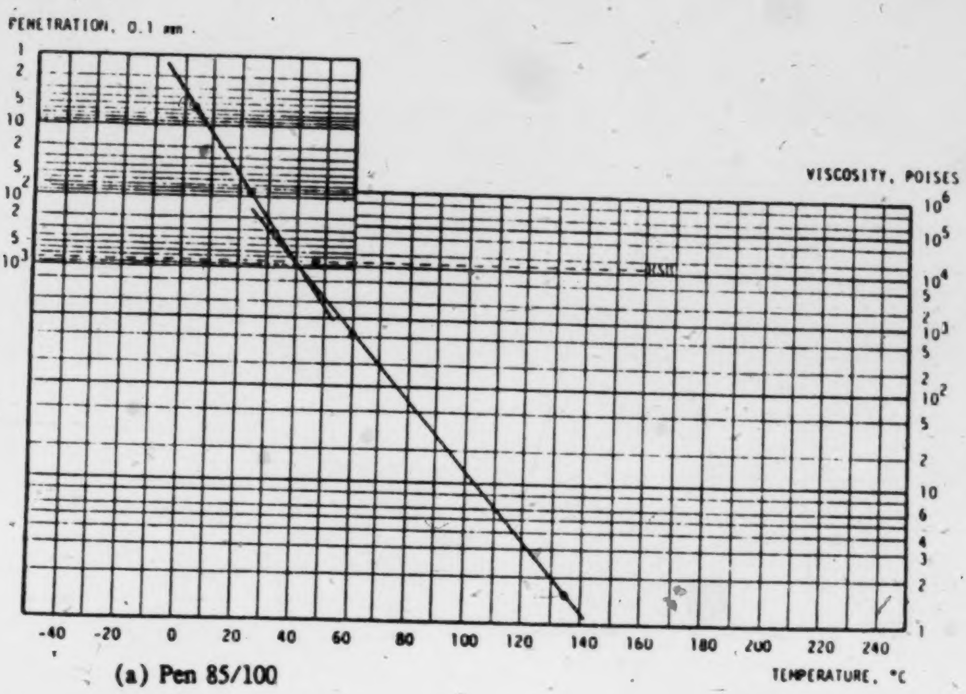


(a) Pen 85/100

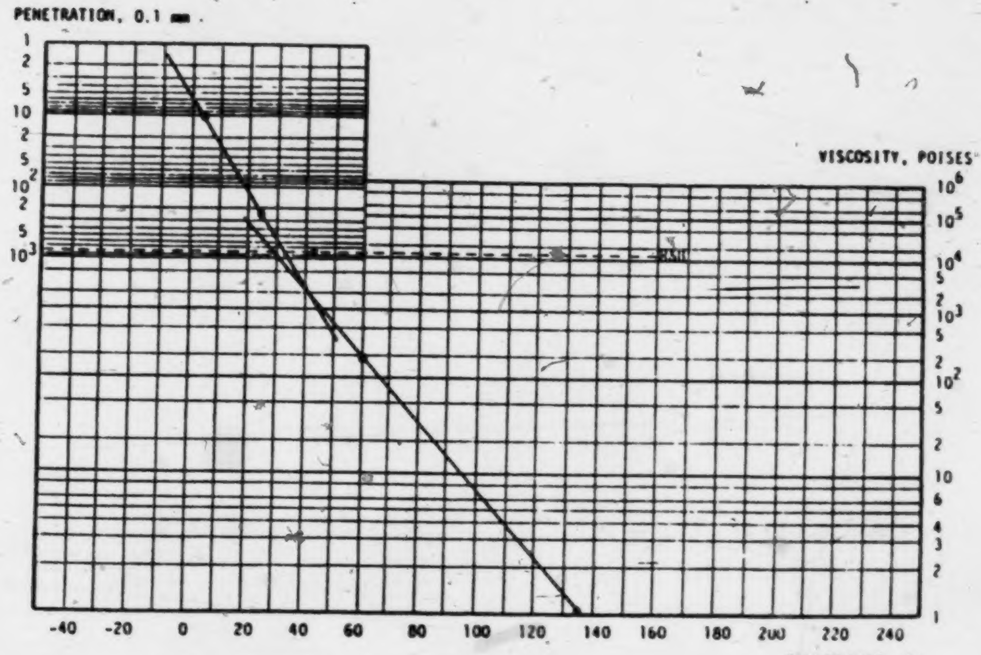


(b) Pen 200/300

Figure 5.4 Bitumen Test Data Charts showing Test Results of Cold Lake Samples



(a) Pen 85/100



(b) Pen 200/300

Figure 5.5 Bitumen Test Data Charts showing Test Results of Redwater Samples

6. TENSILE SPLITTING TEST

6.1 Introduction

Since the early 1960's, research has been ongoing in Alberta on the cracking of asphalt pavements due to thermally induced stresses. One of the important factors in this problem involves the tensile properties of the asphalt concrete pavement at low temperatures that are experienced in the pavement at service temperatures common to Western Canada (25).

The indirect tensile splitting test has been used at the University of Alberta for over twenty years to evaluate the characteristics of laboratory compacted and core specimens from existing pavements. One of the first detailed descriptions of the equipment and test method used then was presented to the AAPT annual meeting in 1968 (19). Since that time the test method has been used to evaluate asphalt concrete prepared from a variety of asphalt cement and aggregate combinations (25,26)

In addition to many highway sections in Alberta, cores have been tested from the Ste. Anne test road in Manitoba. Data from this test road, as well as many others, has led to the development of methods to evaluate the cracking potential of asphalt pavements due to thermally induced stresses. One such method is known as the COLD program (Computation of Low Temperature Damage) developed for the NCHRP project 1-10B (21,22).

The current study of the low temperature tensile properties of asphalt concrete mixtures using asphalt cements from different crude sources has also employed this method with an improved data acquisition and processing system using microcomputer technology.

While the test result of this study will be the major content of this chapter, more detailed description of the testing procedures and apparatus has been included in Appendix D.

6.2 Summary of Method

The tensile splitting test method consists of loading an asphalt concrete cylinder via loading strips across a diameter, in a compression testing frame and within a controlled temperature chamber maintained at a constant low temperature. Output signals from a load cell and three linear variable differential transformers, are recorded on floppy diskette by means of a datalog card installed on a microcomputer. Figure 6.3 shows the schematic of the test equipment layout.

By the use of the Lotus 1-2-3 spreadsheet program, the raw data recorded in the diskette can be processed and the tensile failure stress, strain, stiffness and stress-strain diagram are obtained.

6.3 Theory

The solution of the tensile splitting test is based on the theory of elasticity. Briefly, in a plane stress condition, the stress distribution within a cyclindrical disc subjected to concentrated load (or a load strip of width less than d/10) is both compressive and tensile as shown in Figure 6.2 and 6.3.

The induced tensile stress at the centre of the cylinder is given by the following equation:

$$T = \frac{2 * P}{\pi * d * t} \qquad [6.1]$$

where

T = Induced tensile stress (kPa)
P = Applied load (kN)
d = Diameter of specimen (m)
t = Thickness of specimen (m)

More details of the theory of the tensile splitting test can be found in the references (19,27).

6.4 Laboratory Asphalt Concrete Specimen

Two grades of asphalt cements from three different crude sources were used in preparing the laboratory specimens. The rheological properties and temperature susceptibilities of these different asphalt cements have been described in Chapter 5.

The laboratory specimens were prepared from locally available aggregates, TBG-Clover Bar 12.5mm crushed gravel. The gradation of this aggregate is given in Table 6.1.

Based on the standard Marshall design procedures, (ASTM D1559) an asphalt content of six percent by weight of aggregate was chosen as an approximate optimum content for the asphalt concrete mixtures. Twenty Marshall briquette specimens were fabricated with each of the six different asphalt cements. Each specimen was fabricated under the same conditions, that is, 50 hammer blows at each end of specimen and a compaction temperature of 130 C and 135 C respectively for 200/300 and 85/100 grade asphalts.

The bulk specific gravity of each specimen was then determined by weighing each specimen in air and immersed in water. Groups of five specimens were arranged for testing at different temperatures. They were grouped according to their bulk specific gravities so that each group had similar average density.

6.5 Testing Conditions

The testing was carried out all in accordance with the procedures as described in Appendix D and at temperatures of 0 C, -10 C, -20 C and -30 C.

The loading rate of the testing machine was set at a nominal rate of 1.5 mm/min and kept unchanged throughout.

6.6 Presentation and Discussions of Test Results

6.6.1 Test Results

Table 6.2 summarizes the average stress, strain and secant stiffness modulus of the test specimens at failure. Also, figures 6.4 to 6.6 contain plots of failure stress, failure strain and failure stiffness versus temperature for each of the six different asphalt concrete mixtures. Appendix E contains results of each individual test specimen.

6.6.2 Failure Stress Temperature Relationship

From the tabulated data and plots, it is noted that test temperature has a very significant effect on the failure stress of asphalt concrete mixture.

In general, failure stress increases as test temperature decreases. The trend is particularly apparent at moderate cold temperature, for example 0 C to -10 C. At colder temperature, the rate of the increase of failure stress with decreasing temperature seems to become smaller. From Figure 6.4, it is noted that failure stress ceases to increase as rapidly when test temperature reaches below -10 C and -20 C for 85/100 and 200/300 grade asphalt mixtures respectively.

6.6.3 Failure Strain Temperature Relationship

The failure strain of the test specimens is also affected remarkably by test temperature.

In general, failure strain decreases as test temperature decreases. The rate of the decrease is large as the test temperature changes from 0 C to -10 C. The rate of change becomes smaller as test temperature goes further down. At very cold temperature, for example below -20 C, the asphalt specimens show little strain at failure and the failure strain remains relatively constant.

It seems that there is a critical temperature below which failure strain remains relatively unchanged with dropping temperature. This critical temperature appears to be a function of asphalt grade. For grade 85/100, this temperature is around -20 C and for grade 200/300, it is approximately at -30 C.

6.6.4 Failure Stiffness Temperature Relationship

Failure stiffness generally increases as test temperature decreases.

The 85/100 asphalt has undergone a rapid increase in stiffness when the test temperature dropped from 0 C to -20 C. The increase in stiffness is only slight when the test temperature changed from -20 C to -30 C.

On the contrary, the 200/300 grade asphalt concrete mixtures has undergone very slight increase in stiffness during a drop of test temperature from 0 C to -10 C and a very rapid increase when the test temperature dropped from -20 C to -30 C.

6.6.5 Effect of Crude Source

Figures 6.7 to 6.9 show the average stress strain curves of the test specimens with different crude source asphalts at different test temperatures.

For the 85/100 grade specimens, the average tensile failure stress at 0 C and -10 C is approximately the same irrespective of the crude source. At -20 C and -30 C, the failure stress of the Redwater-Gulf Blend asphalt concrete is lower than that of the Cold Lake and Lloydminster mixtures. However, the average failure strain is markedly smaller for the Redwater-Gulf Blend asphalt concrete mixture. The difference is greater at 0 C and -10 C and becomes negligible at -20 C and colder.

For the 200/300 grade specimen, the average tensile failure stress of the Redwater-Gulf Blend asphalt concrete mixture is higher than that of the Cold Lake and Lloydminster mixtures at 0 C and -10 C. At -20 C and colder temperature, the difference becomes smaller. Similar to the 85/100 grade specimen, the average failure strain of the 200/300 Redwater-Gulf Blend asphalt mixture is markedly smaller than that of the Cold Lake and Lloydminster mixtures. The difference is greater at 0 C to -20 C and becomes almost zero at -30 C.

The stiffness modulus of the Redwater-Gulf Blend asphalt concrete mixture, as shown in Figure 6.6, is slightly higher than that of the Cold Lake and Lloydminster mixtures at most test temperatures.

6.6.6 Effect of Asphalt Grade

By comparing figures 6.4a and 6.4b, it is noted that the failure stress of the softer grade asphalt concrete mixture at 0 C and -10 C is smaller than that of the harder grade mixture. While this phenomenon is not unexpected, it is interesting to note that at -30 C, the phenomenon is reversed and the failure stress of the 200/300 grade mixture is higher than that of the 85/100 grade mixture.

Again, by comparing figures 6.5a and 6.5b, it is noted that the failure strain of the 200/300 grade mixture is generally higher than the 85/100 grade mixture except at test temperature of -30 C. At -30 C, the failure strains of both grades are close.

By comparing figures 6.6a and 6.6b, it is noted that the failure stiffness modulus of the 85/100 grade mixture is greater than that of the 200/300 mixture at test temperature above -20 C. At -30 C, the 200/300 grade mixture becomes stiffer. This is in agreement with the results as discussed in previous paragraphs.

6.7 Low Temperature Performance of Asphalts

On the basis of the results of the laboratory tests to determine the tensile properties of asphalt cements and asphalt concrete mixtures, it is believed that the asphalt cements produced from heavy crude sources of the Cold Lake and Lloydminster areas perform better at low temperature than the specially formulated Redwater-Gulf Blend asphalt cements produced from lighter crude oils.

This conclusion is justified by the results of the tensile splitting test that the Cold Lake and Lloydminster asphalt concrete mixtures can sustain larger strain at failure which is an important property to resist thermally induced cracking (25).

Furthermore, the lower tensile stiffness modulus of the Cold Lake and Lloydminster asphalt concrete mixtures implies that the induced tensile stresses due to temperature change of these mixtures will be smaller. This is advantageous to reduce the chance of thermal cracking because the tensile strength of the mixture will unlikely be exceeded (21).

Based on similar reasoning as above, the performance of the 200/300 grade asphalt at low temperature is better than the 85/100 grade asphalt when both asphalts are produced from the same crude source, that is, of similar temperature susceptibility.

Table 6.1 Aggregate Gradation

Sieve Size (mm)	20	12.5	10.0	5.0	2.0	0.800	0.400	0.160	0.063
% Passing	100	99.8	95.4	70.6	50.6	38.7	28.9	15.8	11.2

Table 6.2 Average Failure Stress, Strain and Stiffness of Test Specimens

Crude Source	Test Temp.	85/100			200/300		
	(°C)	Failure Stress (kPa)	Failure Strain (x 10^{-4})	Failure Stiffness (mPa)	Failure Stress (kPa)	Failure Strain (x 10^{-4})	Failure Stiffness (mPa)
Redwater-Gulf Blend	0	1437	47	624	1049	87	236
	-10	2125	11	3895	2073	17	4706
	-20	2133	4	9639	2703	16	3282
	-30	2177	4	10019	2839	5	10242
Lloydminster	0	1258	102	236	660	140	91
	-10	2352	22	2468	1213	54	431
	-20	2554	7	7259	2815	40	1525
	-30	2406	6	7514	2770	4	12070
Cold Lake	0	1383	68	372	722	121	112
	-10	2179	23	1800	1640	28	1235
	-20	2616	6	8183	2424	21	2253
	-30	2710	6	9231	3013	6	9749

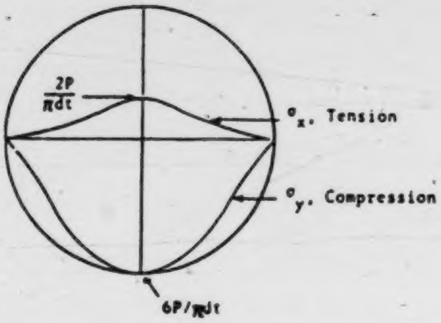

2P
πdt
σx, Tension
σy, Compression
6P/πdt

Figure 6.1 Stress Distribution on x-Axis

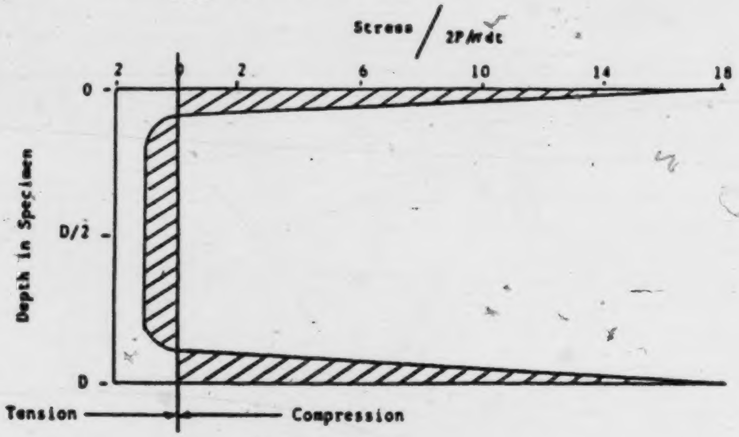


Figure 6.2 Horizontal Stress Distribution on y-Axis

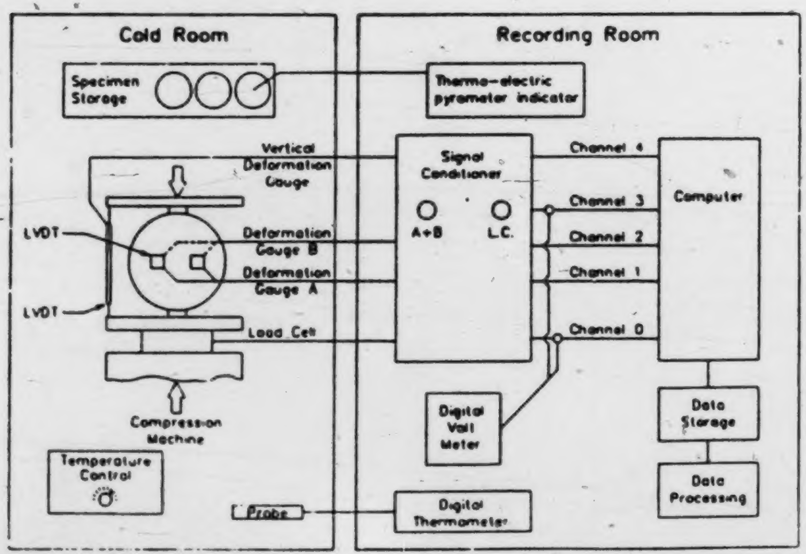
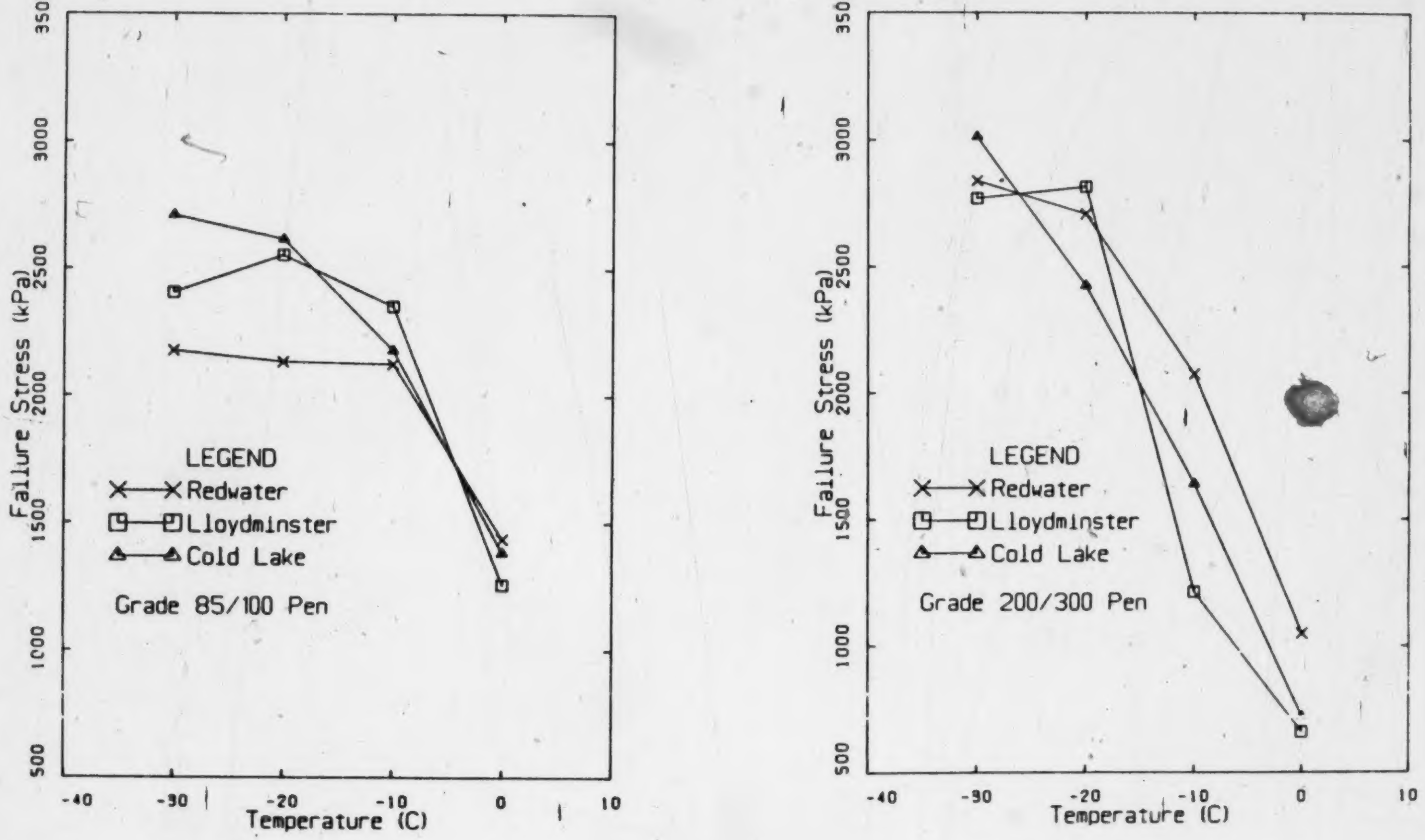

Cold Room
Specimen Storage
Vertical Deformation Gauge
LVDT
Deformation Gauge B
Deformation Gauge A
LVDT
Load Cell
Compression Machine
Temperature Control
Probe
Recording Room
Thermo-electric pyrometer indicator
Signal Conditioner
A+B
L.C.
Channel 4
Channel 3
Channel 2
Channel 1
Channel 0
Computer
Digital Volt Meter
Data Storage
Data Processing
Digital Thermometer

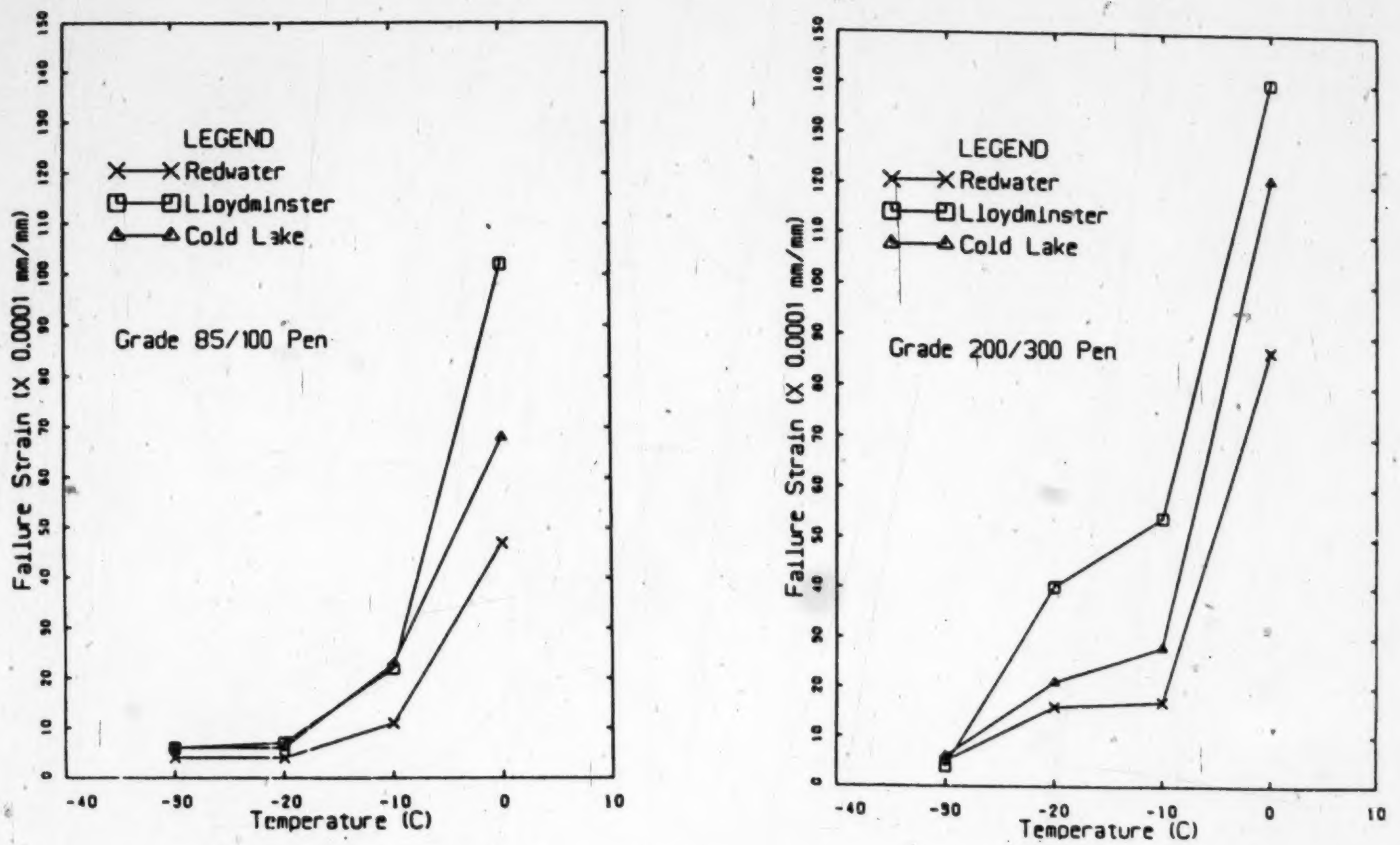
Figure 6.3 Schematic of Test Equipment Layout



(a) Pen 85/100

(b) Pen 200/300

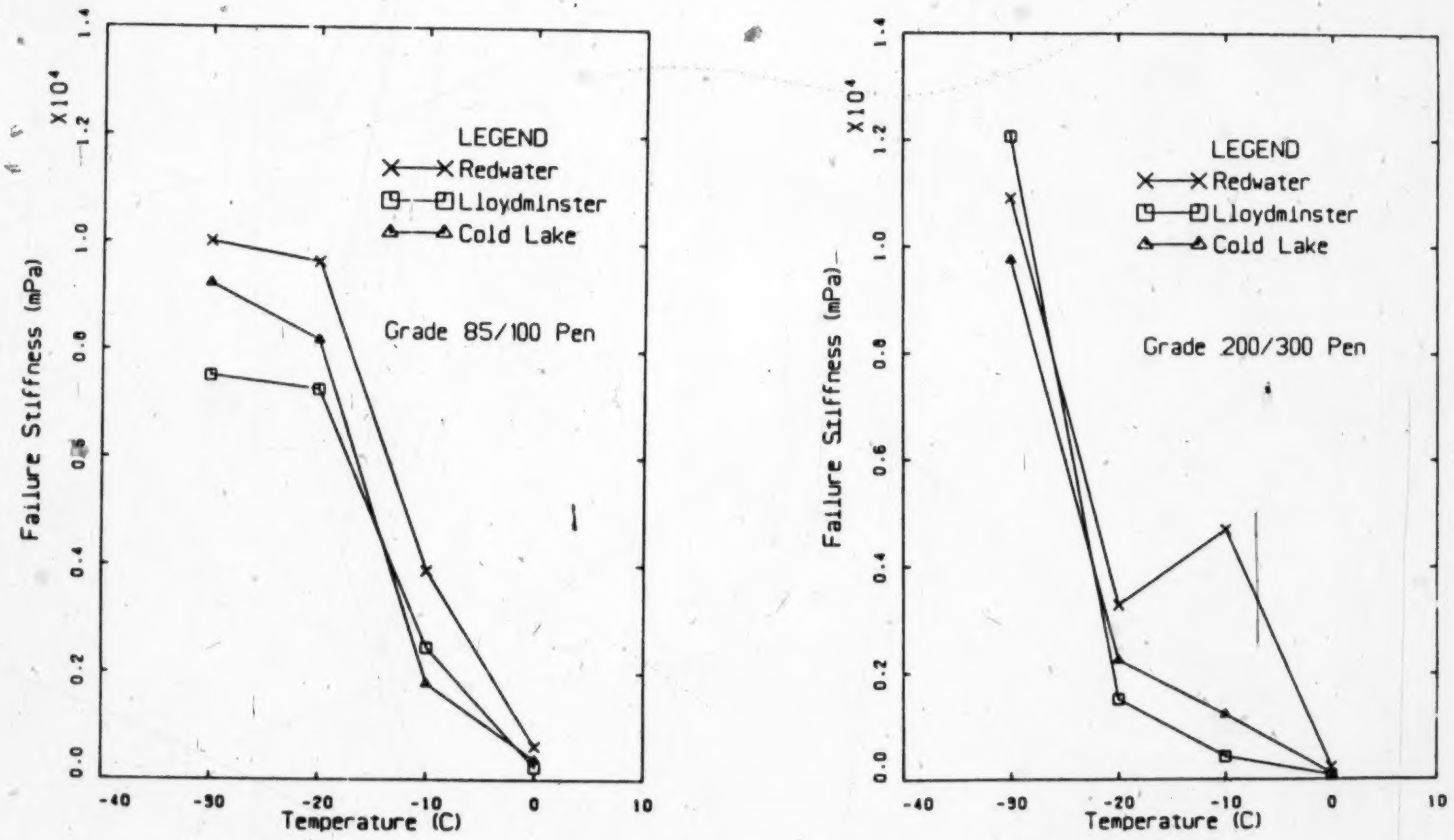
Figure 6.4 Failure Stress- Temperature Relationship



(a) Pen 85/100

(b) Pen 200/300

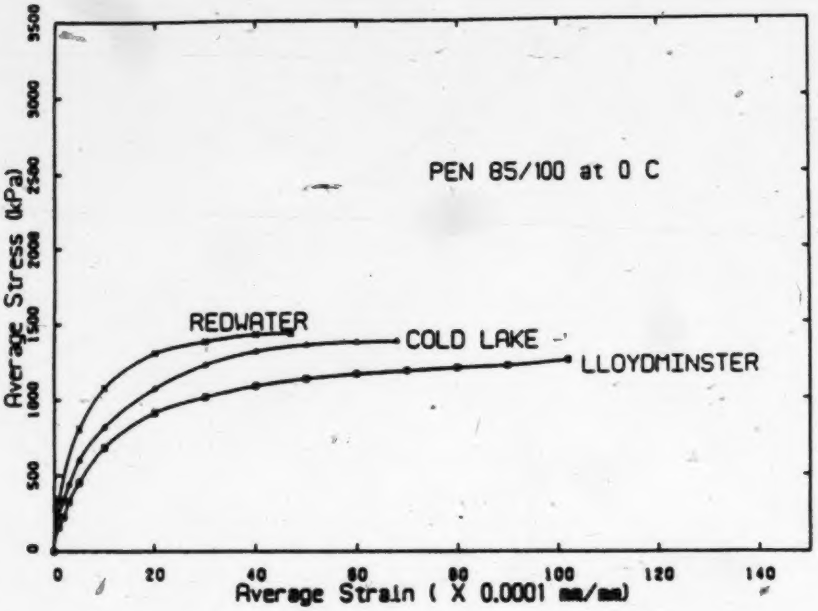
Figure 6.5 Failure Strain - Temperature Relationship



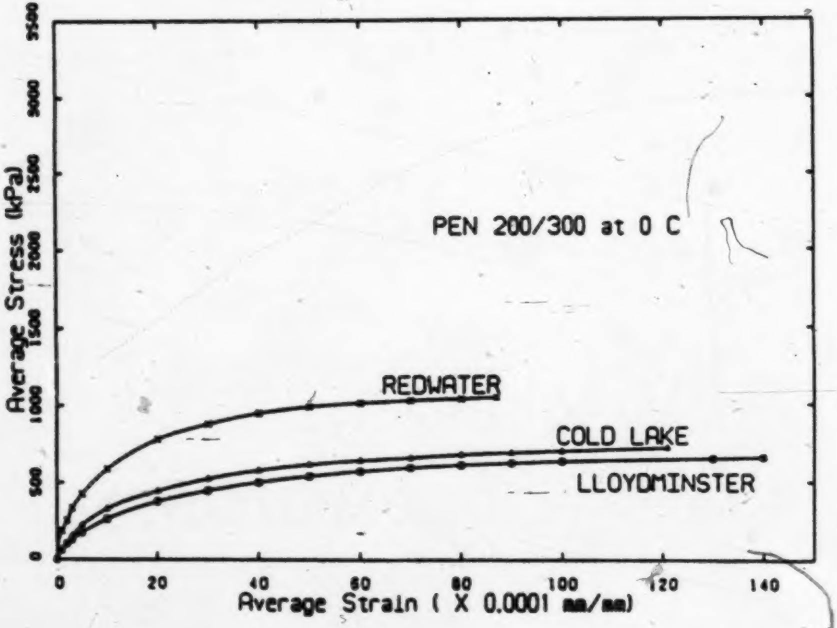
(a) Pen 85/100

(b) Pen 200/300

Figure 6.6 Failure Stiffness - Temperature Relationship

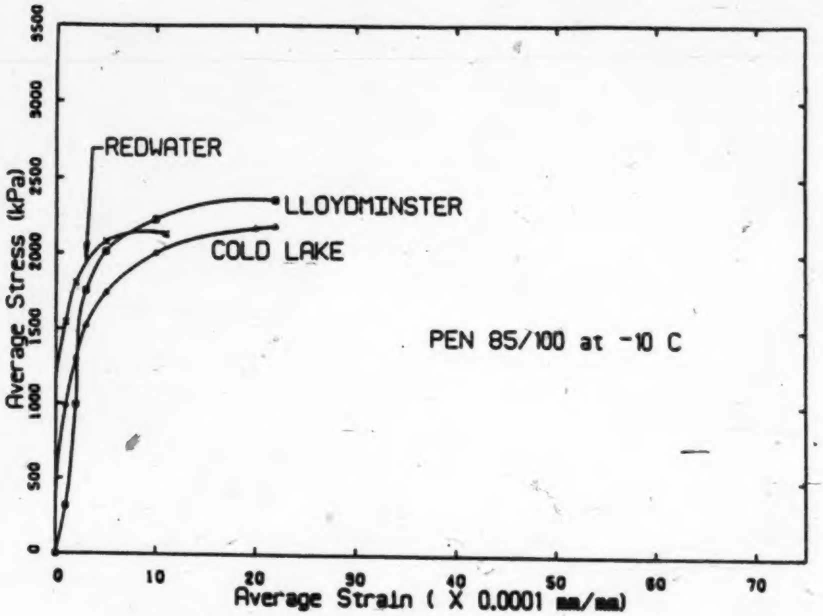


(a) Pen 85/100

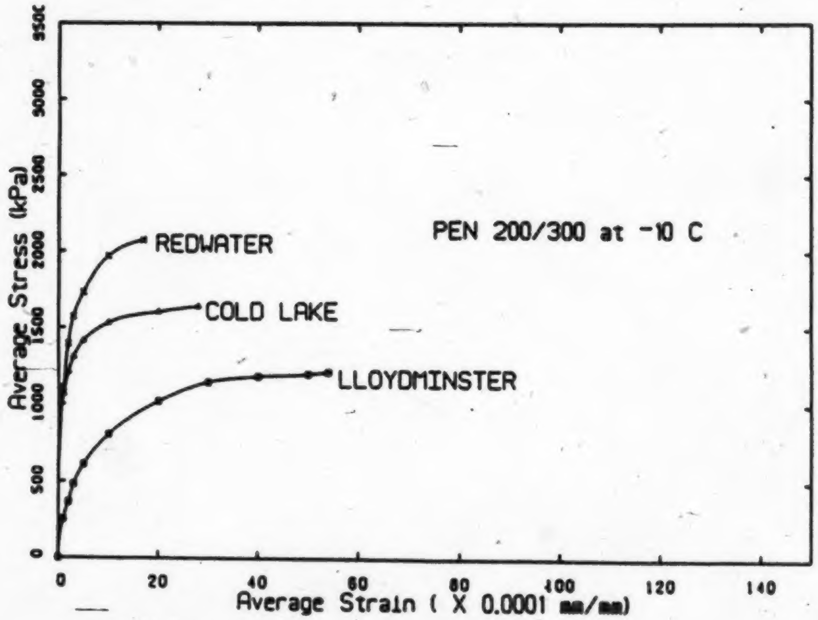


(b) Pen 200/300

Figure 6.7 Average Stress-Strain Curves at 0 C

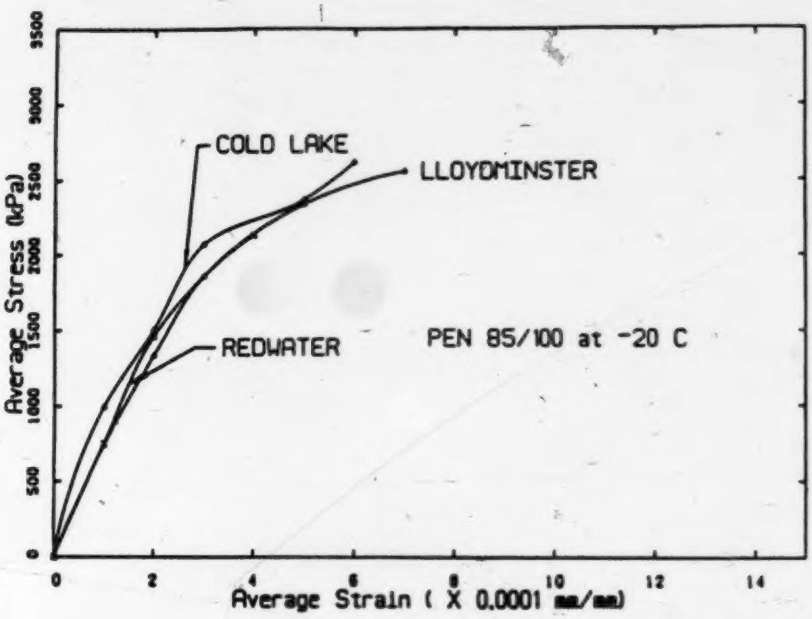


(a) Pen 85/100

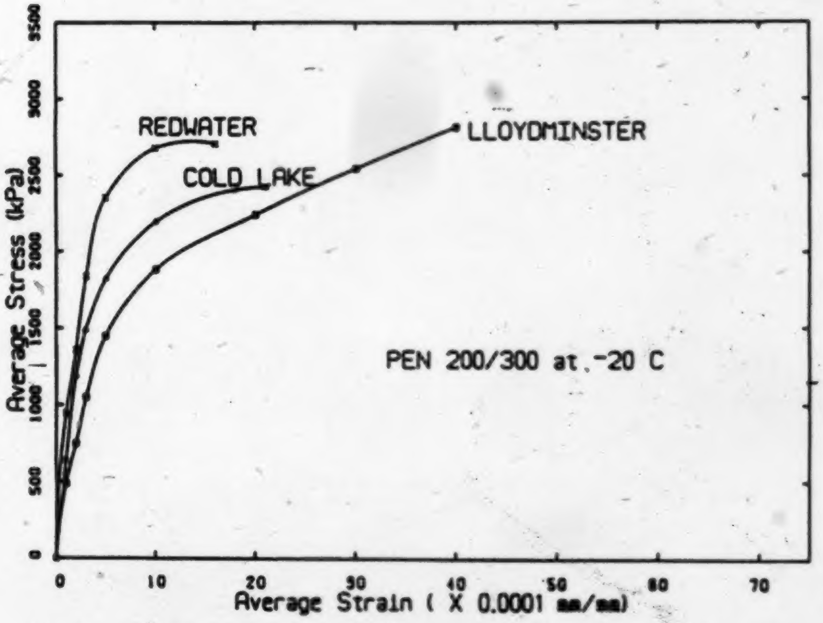


(b) Pen 200/300

Figure 6.8 Average Stress-Strain Curves at -10 C



(a) Pen 85/100



(b) Pen 200/300

Figure 6.9 Average Stress-Strain Curves at -20 C

7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

The following are summarized from the analysis of the 1979 and 1984 as-supplied asphalt cement test data.

1. The 1979 test data shows that the asphalts produced by the Husky Lloydminster refinery are less temperature susceptible than the asphalts produced by Gulf of Moose Jaw and Imperial of Edmonton. The data also shows that the Husky asphalts are more vulnerable to weight loss due to Thin Film Oven Test aging.
2. The 1984 test data shows that the asphalts produced by Husky are less temperature susceptible and have higher resistance to TFOT aging and are less variable.
3. The change of specification in 1980 has affected the properties of asphalts being produced. The overall effect is that the 1984 asphalts have become less temperature susceptible and their variability in properties have also become smaller. Despite the above improvements, however, the durability of most 1984 asphalts has deteriorated slightly except the Husky Lloydminster asphalts.

The following are summarized from the results of the laboratory testing of the asphalt cements produced from three different crude sources.

1. Asphalt cements of the same grade but produced from different crude oils possess different rheological properties. In this study, the properties of the Cold Lake and Lloydminster asphalts are found to be similar. The properties of the Redwater-Gulf Blend asphalt are very different from that of the Cold Lake and Lloydminster Asphalts.
2. The Redwater-Gulf Blend asphalt is the most temperature susceptible among the three different crude source asphalts as shown by all the temperature susceptibility parameters except the PI(R&B). PI(R&B) is not a good temperature susceptibility parameter for the Redwater-Gulf Blend asphalt because of the apparent presence of wax.
3. The temperature susceptibilities of the Cold Lake and Lloydminster asphalts are very similar as shown by the PVN. Other temperature susceptibility parameters show contradictory indication.
4. The PI(dPen/dT) values of the asphalts in the study are more negative than the PVN values indicating that the temperature susceptibilities of these asphalts are greater at low temperature than at high temperature.

The following are summarized from the results of the tensile splitting test on asphalt concrete specimens prepared from asphalts of different crude sources.

1. Tensile failure stress increases with decreasing temperature. The rate of the increase decreases as the temperature continues to drop.
2. Tensile failure strain decreases with decreasing temperature. It appears that there is a critical temperature below which failure strain remains unchanged with decreasing temperature. This critical temperature appears to be a function of asphalt grade. For the 85/100 grade, the critical temperature is around -20 C. For the 200/300 grade, the critical temperature is approximately at -30 C.
3. Asphalt concrete mixtures of the same grade of asphalt but from different crude sources have been shown to possess significantly different tensile properties.In particular, the tensile failure strain of the Redwater-Gulf Blend asphalt concrete mixture is the least of the three different mixtures. The difference diminishes at -20 C and -30 C.
4. Asphalt concrete mixtures with different grades of asphalt have been shown to possess different tensile properties. At 0 C and -10 C, the harder grade asphalt concrete generally has higher failure stress and lower failure strain than the softer grade asphalt concrete.

7.2 Conclusions

The main objective of this research is to evaluate the low temperature performance of asphalt cements produced from different locally available crude sources. This has been achieved by evaluating the historical as-supplied routine asphalt test data followed by the laboratory testing of asphalt cement samples and asphalt concrete specimens.

Based on the results of this study, the following conclusions are drawn.

1. The 1984 asphalt cements have become less temperature susceptible, more uniform, but slightly less durable, when compared with the 1979 asphalts.
2. The specially formulated Redwater-Gulf Blend asphalt cement is expected to have poor low temperature performance, as indicated by the temperature susceptibility parameters, the Bitumen Test Data Chart, the stiffness modulus and the cracking temperature.
3. The Cold Lake and Lloydminster asphalt cements are expected to have similar low temperature performance as indicated by their temperature susceptibilities and tensile properties.
4. Crude source has a significant effect on the low temperature performance of asphalt cements. The asphalt cements produced from heavy crude sources of the Cold Lake and Lloydminster areas perform better at low temperature than the specially formulated asphalt cements produced from lighter crude oils, as indicated

by their different tensile properties.

5. Asphalt grade also has a significant effect on the low temperature performance of asphalt cements. The 200/300 grade asphalt is expected to perform better than the 85/100 grade provided both grades are produced from the same crude source, that is, of similar temperature susceptibility.

7.3 Recommendations for Further Research

The following recommendations for further work are considered worthy to be carried out in order to better understand the low temperature properties of asphalts produced in Western Canada.

1. In the current study, only the original asphalt cements were evaluated with respect to low temperature performance. In order to more closely resemble field conditions, it is recommended that field core samples be obtained and tested. Results of tests can then be correlated to field performance.
2. In evaluating the historical change of asphalt properties, only two sets of data are analysed because these data sets are readily retrievable from the computerized data bank of Alberta Transportation. In order to have a more complete historical review, it is recommended that earlier data be analysed.
3. The tensile splitting test is one of several methods of evaluating low temperature performance of asphalt

cements. Testing techniques to measure temperature-induced stress and fracture temperature have been developed in Hokkaido University of Japan. In order to compare their particular testing method with the tensile splitting test method, it is recommended that these same asphalts be evaluated with their procedures.

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Appendix A

Statistical Summary of As-supplied Asphalt Test Data and Parameters

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                  SOURCE: GULF OIL MOOSEJAW
                  GRADE : AC-60.0              YEAR : 1979
                  CODE  : d-79-1-0

                 VIS@60   VIS@135    PEN@25  %WLOSS    TVIS@60   TPEN@25      PVN@60    PVN@135      TPVN@60     RVIS@60   RPEN@25
                 (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)     (DMM)

NO. OF SAMPLES =    3        3          3      3          3         3            3          3            3           3          3
MEAN VALUE     =  62.87    239.33    195.67  0.485     176.4      99.0     -0.1348    -0.2171      -0.1816      2.7999    0.5057
ST DEVIATION   =   5.39      4.62      4.51  0.074      24.8       6.1      0.0658     0.0194       0.0554      0.1961    0.0210
CO VARIATION   =   0.09      0.02      0.02  0.152       0.14      0.06    -0.4883    -0.0893      -0.3052      0.0700    0.0415
MAX VALUE      =  67.40    242.00    200.00  0.557     203.7     103.0     -0.0930    -0.1948      -0.1413      3.0223    0.5204
MIN VALUE      =  56.90    234.00    191.00  0.410     155.1      92.0     -0.2106    -0.2298      -0.2448      2.6516    0.4817

                  SOURCE: GULF OIL MOOSEJAW
                  GRADE : 150/200A             YEAR : 1979
                  CODE  : d-79-1-1

                 VIS@60   VIS@135    PEN@25  %WLOSS    TVIS@60   TPEN@25      PVN@60    PVN@135      TPVN@60     RVIS@60   RPEN@25
                 (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)     (DMM)

NO. OF SAMPLES =   21       21         21     21         21        21           21         21           21          21         21
MEAN VALUE     =  47.95    198.24    174.38  0.283     137.9      87.8     -0.6709    -0.6951      -0.6609      2.8777    0.5040
ST DEVIATION   =   2.69      4.58      9.61  0.107      21.4      15.1      0.0729     0.0542       0.0937      0.4279    0.0848
CO VARIATION   =   0.06      0.02      0.06  0.379       0.16      0.17    -0.1087    -0.0780      -0.1418      0.1487    0.1683
MAX VALUE      =  53.50    206.00    195.00  0.613     194.8     148.0     -0.4948    -0.6189      -0.4134      3.8422    0.8506
MIN VALUE      =  42.60    187.00    155.00  0.193      76.3      68.0     -0.8063    -0.8107      -0.8094      1.6303    0.4103

                  SOURCE: GULF OIL MOOSEJAW
                  GRADE : AC-1.5               YEAR : 1979
                  CODE  : d-79-1-3

                 VIS@60   VIS@135    PEN@25  %WLOSS    TVIS@60   TPEN@25      PVN@60    PVN@135      TPVN@60     RVIS@60   RPEN@25
                 (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)     (DMM)

NO. OF SAMPLES =    4        4          4      4          4         4            4          4            4           4          4
MEAN VALUE     =  17.20    126.25    361.50  0.457      45.4     175.5     -0.5890    -0.5616      -0.7362      2.6330    0.4859
ST DEVIATION   =   1.43      7.50     19.74  0.064       8.1       6.6      0.0722     0.0525       0.1620      0.3713    0.0120
CO VARIATION   =   0.08      0.06      0.05  0.139       0.18      0.04    -0.1225    -0.0934      -0.2201      0.1410    0.0247
MAX VALUE      =  18.80    134.00    379.00  0.535      56.4     182.0     -0.5098    -0.4968      -0.4992      3.1864    0.5029
MIN VALUE      =  15.40    118.00    342.00  0.386      38.3     168.0     -0.6569    -0.6253      -0.8594      2.3905    0.4749
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          SOURCE: HUSKY OIL LLOYDMINSTER
          GRADE : AC-60.0                  YEAR : 1979
          CODE  : d-79-2-0

         VIS@60   VIS@135     PEN@25  %WLOSS    TVIS@60   TPEN@25      PVN@60   PVN@135      TPVN@60     RVIS@60    RPEN@25
         (PA.S) (CENTISTOKE) (DMM)     (%)      (PA.S)     (DMM)

NO. OF SAMPLES =  18      18       18     18        18        18          18        18          18          18         18
MEAN VALUE     =  82.98   266.67   180.94  0.553    197.4     97.6     -0.0419   -0.2014     -0.1096      2.4059     0.5643
ST DEVIATION   =  15.83    45.27    59.80  0.356     37.3      9.6      0.1184    0.2686      0.2861      0.2389     0.0978
CO VARIATION   =   0.19     0.17     0.33  0.645      0.19     0.10    -2.8223   -1.3335     -2.6105      0.0993     0.1734
MAX VALUE      =  93.80   344.00   417.00  1.952    242.8    131.0      0.3296    0.4181      0.5910      3.0515     0.7988
MIN VALUE      =  23.30   147.00   147.00  0.364     71.1     87.0     -0.1876   -1.0420     -1.0172      2.0248     0.2590

          SOURCE: HUSKY OIL LLOYDMINSTER
          GRADE : AC-27.5                  YEAR : 1979
          CODE  : d-79-2-2

         VIS@60   VIS@135     PEN@25  %WLOSS    TVIS@60   TPEN@25      PVN@60   PVN@135      TPVN@60     RVIS@60    RPEN@25
         (PA.S) (CENTISTOKE) (DMM)     (%)      (PA.S)     (DMM)

NO. OF SAMPLES =  126     126      126    124       124       124         126       126         124         124        124
MEAN VALUE     =  43.31   200.39   276.02  0.858    110.4    141.0      0.0801   -0.0529     -0.0847      2.5540     0.5123
ST DEVIATION   =   2.90     7.23    13.46  0.156     11.6      8.9      0.0626    0.0596      0.0762      0.2818     0.0339
CO VARIATION   =   0.07     0.04     0.05  0.182      0.10     0.06     0.7820   -1.1258     -0.9001      0.1103     0.0663
MAX VALUE      =  52.90   222.00   327.00  1.474    141.0    172.0      0.2452    0.1911      0.1520      3.8927     0.5985
MIN VALUE      =  31.70   172.00   244.00  0.651     81.3    115.0     -0.1834   -0.2766     -0.4484      1.9403     0.4078
          SOURCE: HUSKY OIL LLOYDMINSTER
          GRADE : AC-20.0                  YEAR : 1979
          CODE  : d-79-2-5

         VIS@60   VIS@135     PEN@25  %WLOSS    TVIS@60   TPEN@25      PVN@60   PVN@135      TPVN@60     RVIS@60    RPEN@25
         (PA.S) (CENTISTOKE) (DMM)     (%)      (PA.S)     (DMM)

NO. OF SAMPLES =  29      29       29     29        29        29          29        29          29          29         29
MEAN VALUE     =  27.08   161.62   376.66  1.261     72.3    187.4      0.1191    0.0095     -0.0537      2.6666     0.4997
ST DEVIATION   =   1.36     5.29    25.81  0.143      6.9     10.8      0.1417    0.1200      0.0753      0.1941     0.0448
CO VARIATION   =   0.05     0.03     0.07  0.114      0.09     0.06     1.1897   12.5859     -1.4031      0.0728     0.0897
MAX VALUE      =  30.20   168.00   427.00  1.607     85.9    221.0      0.2775    0.1425      0.0461      2.9826     0.6970
MIN VALUE      =  23.70   149.00   264.00  1.093     56.2    166.0     -0.5106   -0.4834     -0.3172      2.2953     0.4392
```

```
                 SOURCE: IMPERIAL OIL EDMONTON
                 GRADE : AC-60.0              YEAR : 1979
                 CODE  : d-79-3-0

                 VIS@60  VIS@135     PEN@25  %WLOSS   TVIS@60   TPEN@25    PVN@60    PVN@135    TPVN@60    RVIS@60   RPEN@25
                 (PA.S) (CENTISTOKE) (DMM)    (%)     (PA.S)     (DMM)

NO. OF SAMPLES =   65       65         65      62        62        62         65         65         62         62        62
MEAN VALUE     =  73.41    247.25    170.12   0.380    182.1      93.3    -0.2111    -0.3491    -0.2494     2.4871    0.5501
ST DEVIATION   =   4.28     12.98      7.76   0.071     21.7       7.0     0.0858     0.1018     0.1102     0.3024    0.0489
CO VARIATION   =   0.06      0.05      0.05   0.186      0.12      0.07   -0.4066    -0.2917    -0.4419     0.1216    0.0889
MAX VALUE      =  85.80    272.00    187.00   0.597    257.1     116.0    -0.0028    -0.1674     0.1629     3.3632    0.6824
MIN VALUE      =  57.00    167.00    153.00   0.244    144.1      74.0    -0.4058    -0.9710    -0.4890     2.0098    0.4205

                 SOURCE: IMPERIAL OIL EDMONTON
                 GRADE : 150/200A             YEAR : 1979
                 CODE  : d-79-3-1

                 VIS@60  VIS@135     PEN@25  %WLOSS   TVIS@60   TPEN@25    PVN@60    PVN@135    TPVN@60    RVIS@60   RPEN@25
                 (PA.S) (CENTISTOKE) (DMM)    (%)     (PA.S)     (DMM)

NO. OF SAMPLES =   35       35         35      35        35        35         35         35         35         35        35
MEAN VALUE     =  43.21    199.57    177.49   0.092     83.5     108.1    -0.7836    -0.6755    -0.8815     1.9076    0.6160
ST DEVIATION   =   6.42     17.62     27.43   0.124     25.3      12.2     0.2465     0.1904     0.1639     0.2520    0.0702
CO VARIATION   =   0.15      0.09      0.15   1.347      0.30      0.11   -0.3146    -0.2819    -0.1859     0.1321    0.1140
MAX VALUE      =  70.80    249.00    292.00   0.556    209.4     135.0     0.0959    -0.0773    -0.2817     2.9576    0.7746
MIN VALUE      =  34.70    164.00    139.00   0.008     55.3      83.0    -1.1448    -0.9654    -1.1649     1.5665    0.3870

                 SOURCE: IMPERIAL OIL EDMONTON

                 GRADE : AC-27.5              YEAR : 1979
                 CODE  : d-79-3-2

                 VIS@60  VIS@135     PEN@25  %WLOSS   TVIS@60   TPEN@25    PVN@60    PVN@135    TPVN@60    RVIS@60   RPEN@25
                 (PA.S) (CENTISTOKE) (DMM)    (%)     (PA.S)     (DMM)

NO. OF SAMPLES =  241      241        241     234       234       234        241        241        234        234       234
MEAN VALUE     =  34.50    174.34    290.57   0.630     82.9     150.2    -0.1154    -0.2500    -0.3082     2.4045    0.5188
ST DEVIATION   =   3.36     13.97     22.36   0.188     11.5      12.7     0.0775     0.1492     0.0666     0.2696    0.0395
CO VARIATION   =   0.10      0.08      0.08   0.298      0.14      0.08   -0.6711    -0.5965    -0.2161     0.1121    0.0761
MAX VALUE      =  47.30    261.00    427.00   1.840    124.2     181.0     0.2029     0.5580    -0.0090     3.6396    0.6000
MIN VALUE      =  19.30     89.00    220.00   0.379     58.5     110.0    -0.3616    -1.6612    -0.5672     1.9740    0.3782
```

```
                  SOURCE: GULF OIL CALGARY
                  GRADE : AC-60.0            YEAR : 1979
                  CODE  : d-79-5-0

                VIS@60   VIS@135     PEN@25  %WLOSS   TVIS@60  TPEN@25    PVN@60   PVN@135    TPVN@60   RVIS@60   RPEN@25
                (PA.S) (CENTISTOKE)  (DMM)     (%)     (PA.S)   (DMM)

NO. OF SAMPLES =  29      29           29     29        29       29        29        29         29        29        29
MEAN VALUE     =  62.34   234.07      182.07  0.182    135.0    103.7    -0.2913   -0.3625    -0.3905    2.1944    0.5746
ST DEVIATION   =   6.78    22.33       18.91  0.248     12.4      5.9     0.0836    0.1464     0.0438    0.3787    0.0572
CO VARIATION   =   0.11     0.10        0.10  1.363      0.09     0.06   -0.2870   -0.4038    -0.1122    0.1726    0.0995
MAX VALUE      =  72.80   338.00      268.00  1.377    164.6    117.0    -0.0552    0.2939    -0.3217    3.9533    0.6442
MIN VALUE      =  40.70   201.00      163.00  0.047    109.8     89.0    -0.4175   -0.5073    -0.4705    1.9082    0.3433
                  SOURCE: GULF OIL CALGARY
                  GRADE : AC-27.5            YEAR : 1979
                  CODE  : d-79-5-2

                VIS@60   VIS@135     PEN@25  %WLOSS   TVIS@60  TPEN@25    PVN@60   PVN@135    TPVN@60   RVIS@60   RPEN@25
                (PA.S) (CENTISTOKE)  (DMM)     (%)     (PA.S)   (DMM)

NO. OF SAMPLES =  10      10           10      8         8        8        10        10          8         8         8
MEAN VALUE     =  31.48   165.40      287.50  0.251     73.3    155.1    -0.2546   -0.3647    -0.3856    2.3129    0.5565
ST DEVIATION   =   2.21     7.96       29.69  0.158      8.7      9.6     0.1720    0.1025     0.0497    0.3331    0.0389
CO VARIATION   =   0.07     0.05        0.10  0.630      0.12     0.06   -0.6755   -0.2811    -0.1290    0.1440    0.0699
MAX VALUE      =  33.70   182.00      336.00  0.607     91.4    164.0    -0.0581   -0.2205    -0.3295    3.0467    0.6007
MIN VALUE      =  27.90   155.00      241.00  0.114     66.9    138.0    -0.6502   -0.5011    -0.4575    2.0089    0.4792
```

```
                  SOURCE: ALL SOURCES
                  GRADE  : AC60.0              YEAR : 1979
                  CODE   : d-79-0

                 VIS•60  VIS•135      PEN•25  %WLOSS   TVIS•60   TPEN•25     PVN•60    PVN•135     TPVN•60    RVIS•60   RPEN•25
                 (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)     (DMM)

NO. OF SAMPLES =  115       115        115     112       112       112         115        115         112        112       112
MEAN VALUE     =  71.84    246.76     175.50  0.359     172.2      96.8     -0.2028    -0.3259     -0.2616     2.4066    0.5575
ST DEVIATION   =  10.27     25.06      26.42  0.230      32.3       8.4      0.1194     0.1589      0.1676     0.3398    0.0616
CO VARIATION   =   0.14      0.10       0.15  0.639       0.19      0.09    -0.5886    -0.4876     -0.6406     0.1412    0.1106
MAX VALUE      =  93.80    344.00     417.00  1.952     257.1     131.0      0.3296     0.4181      0.5910     3.9533    0.7988
MIN VALUE      =  23.30    147.00     147.00  0.047      71.1      74.0     -0.4175    -1.0420     -1.0172     1.9082    0.2590
                  SOURCE: ALL SOURCES
                  GRADE  : 150/200A             YEAR : 1979
                  CODE   : d-79-1

                 VIS•60  VIS•135      PEN•25  %WLOSS   TVIS•60   TPEN•25     PVN•60    PVN•135     TPVN•60    RVIS•60   RPEN•25
                 (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)     (DMM)

NO. OF SAMPLES =   56        56         56     56         56        56          56         56          56         56        56
MEAN VALUE     =  44.99    199.07     176.32  0.164     103.9     100.5     -0.7414    -0.6828     -0.7988     2.2714    0.5740
ST DEVIATION   =   5.79     14.14      22.39  0.150      35.6      16.5      0.2062     0.1536      0.1772     0.5748    0.0931
CO VARIATION   =   0.13      0.07       0.13  0.914       0.34      0.16    -0.2782    -0.2249     -0.2219     0.2531    0.1621
MAX VALUE      =  70.80    249.00     292.00  0.613     209.4     148.0      0.0959    -0.0773     -0.2817     3.8422    0.8506
MIN VALUE      =  34.70    164.00     139.00  0.008      55.3      68.0     -1.1448    -0.9654     -1.1649     1.5665    0.3870

                  SOURCE: ALL SOURCES
                  GRADE  : AC27.5              YEAR : 1979
                  CODE   : d-79-2

                 VIS•60  VIS•135      PEN•25  %WLOSS   TVIS•60   TPEN•25     PVN•60    PVN•135     TPVN•60    RVIS•60   RPEN•25
                 (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)     (DMM)

NO. OF SAMPLES =  377       377        377     366       366       366         377        377         366        366       366
MEAN VALUE     =  37.36    182.81     285.63  0.699      92.0     147.2     -0.0538    -0.1872     -0.2341     2.4531    0.5174
ST DEVIATION   =   5.30     17.35      21.14  0.217      17.5      12.3      0.1239     0.1583      0.1282     0.2840    0.0381
CO VARIATION   =   0.14      0.09       0.07  0.311       0.19      0.08    -2.3046    -0.8454     -0.5476     0.1158    0.0737
MAX VALUE      =  52.90    261.00     427.00  1.840     141.0     181.0      0.2452     0.5580      0.1520     3.8927    0.6007
MIN VALUE      =  19.30     89.00     220.00  0.114      58.5     110.0     -0.6502    -1.6612     -0.5672     1.9403    0.3782
```

SOURCE: HUSKY OIL LLOYDMINSTER
GRADE : 150/200A YEAR : 1984
CODE : d-84-2-1

	VIS@60 (PA.S)	VIS@135 (CENTISTOKE)	PEN@25 (DMM)	%WLOSS (%)	TVIS@60 (PA.S)	TPEN@25 (DMM)	PVN@60	PVN@135	TPVN@60	RVIS@60	RPEN@25
NO. OF SAMPLES =	147	147	147	93	93	93	147	147	93	93	93
MEAN VALUE =	81.47	272.75	168.70	0.309	188.5	97.4	-0.1072	-0.1926	-0.1405	2.3002	0.5787
ST DEVIATION =	6.60	13.49	11.05	0.129	19.9	8.2	0.0971	0.0901	0.1131	0.2342	0.0466
CO VARIATION =	0.08	0.05	0.07	0.416	0.11	0.08	-0.9058	-0.4679	-0.8050	0.1018	0.0805
MAX VALUE =	108.70	315.00	227.00	1.248	245.1	125.0	0.1000	-0.0163	0.3527	3.1667	0.7440
MIN VALUE =	55.00	204.00	141.00	0.074	130.0	82.0	-0.3184	-0.6969	-0.3840	1.5682	0.4493

SOURCE: HUSKY OIL LLOYDMINSTER
GRADE : 200/300A YEAR : 1984
CODE : d-84-2-2

	VIS@60 (PA.S)	VIS@135 (CENTISTOKE)	PEN@25 (DMM)	%WLOSS (%)	TVIS@60 (PA.S)	TPEN@25 (DMM)	PVN@60	PVN@135	TPVN@60	RVIS@60	RPEN@25
NO. OF SAMPLES =	120	120	120	90	90	90	120	120	90	90	90
MEAN VALUE =	42.56	200.69	275.55	0.608	105.3	146.6	0.0543	-0.0543	-0.0681	2.4620	0.5287
ST DEVIATION =	2.95	11.24	15.27	0.194	10.3	8.9	0.1281	0.1136	0.1261	0.2334	0.0409
CO VARIATION =	0.07	0.06	0.06	0.318	0.10	0.06	2.3579	-2.0916	-1.8523	0.0948	0.0774
MAX VALUE =	54.60	252.00	353.00	1.571	130.4	175.0	0.6097	0.2919	0.1997	3.2500	0.6458
MIN VALUE =	32.90	162.00	250.00	0.322	83.2	130.0	-0.2245	-0.4052	-0.3607	2.0442	0.4187

SOURCE: HUSKY OIL LLOYDMINSTER
GRADE : 300/400A YEAR : 1984
CODE : d-84-2-3

	VIS@60 (PA.S)	VIS@135 (CENTISTOKE)	PEN@25 (DMM)	%WLOSS (%)	TVIS@60 (PA.S)	TPEN@25 (DMM)	PVN@60	PVN@135	TPVN@60	RVIS@60	RPEN@25
NO. OF SAMPLES =	31	31	31	23	23	23	31	31	23	23	23
MEAN VALUE =	27.95	164.45	358.16	0.878	69.6	184.2	0.0536	-0.0358	-0.1311	2.5081	0.5135
ST DEVIATION =	1.71	6.11	17.66	0.197	6.8	12.3	0.1237	0.1003	0.1335	0.2588	0.0360
CO VARIATION =	0.06	0.04	0.05	0.225	0.10	0.07	2.3056	-2.7977	-1.0184	0.1032	0.0702
MAX VALUE =	33.70	178.00	395.00	1.496	85.8	208.0	0.2857	0.2088	0.2227	3.0083	0.6172
MIN VALUE =	24.10	152.00	303.00	0.688	52.6	167.0	-0.3297	-0 3454	-0.4210	1.8456	0.4516

```
                    SOURCE: GULF OIL MOOSE JAW
                    GRADE  : 150/200A              YEAR : 1984
                    CODE   : d-84-1-1

                 VIS@60   VIS@135      PEN@25  %WLOSS    TVIS@60   TPEN@25     PVN@60    PVN@135     TPVN@60    RVIS@60    RPEN@25
                 (PA.S) (CENTISTOKE) (DMM)      (%)      (PA.S)    (DMM)

NO. OF SAMPLES =    8        8          8        8          8         8           8          8           8          8          8
MEAN VALUE     =  67.32    237.75     207.88   0.599      178.4      99.9      0.0023    -0.1782     -0.1483     2.8003     0.4950
ST DEVIATION   =  14.65     25.56      48.04   0.564       12.1       3.7      0.1194     0.0876      0.0371     0.8474     0.0725
CO VARIATION   =   0.22      0.11       0.23   0.942        0.07      0.04    51.5719    -0.4919     -0.2502     0.3026     0.1465
MAX VALUE      =  82.50    272.00     323.00   1.960      202.2     104.0      0.1811     0.0269     -0.1004     4.8472     0.5509
MIN VALUE      =  36.00    184.00     167.00   0.317      158.5      92.0     -0.1287    -0.2496     -0.2213     2.1297     0.3220

                    SOURCE: GULF OIL MOOSE JAW
                    GRADE  : 200/300A              YEAR : 1984
                    CODE   : d-84-1-2

                 VIS@60   VIS@135      PEN@25  %WLOSS    TVIS@60   TPEN@25     PVN@60    PVN@135     TPVN@60    RVIS@60    RPEN@25
                 (PA.S) (CENTISTOKE) (DMM)      (%)      (PA.S)    (DMM)

NO. OF SAMPLES =    3        3          3        1          1         1           3          3           1          1          1
MEAN VALUE     =  45.60    209.00     243.67   0.742      107.6     118.0     -0.1022    -0.1553     -0.4162     2.4289     0.4777
ST DEVIATION   =   1.25      4.36       4.93   0.0          0.0       0.0      0.0194     0.0290      0.0        0.0        0.0
CO VARIATION   =   0.03      0.02       0.02   0.0          0.0       0.0     -0.1900    -0.1871      0.0        0.0        0.0
MAX VALUE      =  46.80    212.00     247.00   0.742      107.6     118.0     -0.0800    -0.1234     -0.4162     2.4289     0.4777
MIN VALUE      =  44.30    204.00     238.00   0.742      107.6     118.0     -0.1156    -0.1802     -0.4162     2.4289     0.4777
```

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               SOURCE: IMPERIAL OIL EDMONTON
               GRADE : 150/200A                 YEAR : 1984
               CODE  : d-84-3-1

              VIS@60  VIS@135      PEN@25  %WLOSS   TVIS@60  TPEN@25     PVN@60    PVN@135     TPVN@60    RVIS@60   RPEN@25
              (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)    (DMM)

NO. OF SAMPLES =  113     113        113     82        82       82         113        113          82         82        82
MEAN VALUE     =  79.95   258.67     160.21  0.554     222.0    82.9      -0.2258    -0.3515     -0.2414     2.7594    0.5112
ST DEVIATION   =   8.16    17.02      11.29  0.147      36.8     7.4       0.1375     0.1172      0.0982     0.3547    0.0361
CO. VARIATION  =   0.10     0.07       0.07  0.266       0.17    0.09     -0.6087    -0.3335     -0.4068     0.1285    0.0707
MAX VALUE      = 114.90   306.00     208.00  1.291     348.8   102.0       0.2023     0.0017      0.0528     4.0498    0.5652
MIN VALUE      =  60.20   197.00     144.00  0.313     161.4    67.0      -0.4867    -0.7853     -0.4176     2.0584    0.4136
1
               SOURCE: IMPERIAL OIL EDMONTON
               GRADE : 200/300A                 YEAR : 1984
               CODE  : d-84-3-2

              VIS@60  VIS@135      PEN@25  %WLOSS   TVIS@60  TPEN@25     PVN@60    PVN@135     TPVN@60    RVIS@60   RPEN@25
              (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)    (DMM)

NO. OF SAMPLES =  168     168        168     117       117      117        168        168         117        117       117
MEAN VALUE     =  44.62   198.82     233.93  0.708     119.1    114.7     -0.2227    -0.3126     -0.3688     2.6465    0.4922
ST DEVIATION   =   5.74    15.33      15.70  0.138      18.5     8.8       0.1040     0.0999      0.1027     0.2900    0.0350
CO VARIATION   =   0.13     0.08       0.07  0.195       0.15    0.08     -0.4670    -0.3194     -0.2784     0.1096    0.0711
MAX VALUE      =  66.70   287.00     277.00  1.318     200.6   133.0       0.2414     0.2132     -0.1340     3.8436    0.5829
MIN VALUE      =  32.50   173.00     187.00  0.368      88.7    91.0      -0.4565    -0.4999     -0.5887     1.9620    0.3755

               SOURCE: SHELL OIL THREE CREEK
               GRADE : 200/300B                 YEAR : 1984
               CODE  : d-84-4-4

              VIS@60  VIS@135      PEN@25  %WLOSS   TVIS@60  TPEN@25     PVN@60    PVN@135     TPVN@60    RVIS@60   RPEN@25
              (PA.S) (CENTISTOKE) (DMM)     (%)     (PA.S)    (DMM)

NO. OF SAMPLES =  13      13         13      13        13       13         13         13          13         13        13
MEAN VALUE     =  48.71   194.69     225.54  2.797     215.4    80.9      -0.1966    -0.4070     -0.3152     4.4518    0.3611
ST DEVIATION   =   7.07    15.98      27.27  0.493      36.3     7.9       0.1091     0.1069      0.0992     0.6283    0.0371
CO VARIATION   =   0.15     0.08       0.12  0.176       0.17    0.10     -0.5547    -0.2625     -0.3148     0.1411    0.1028
MAX VALUE      =  53.60   211.00     293.00  3.908     268.4    97.0      -0.0481    -0.2877     -0.0416     5.7910    0.4356
MIN VALUE      =  33.50   158.00     200.00  1.844     144.5    66.0      -0.3467    -0.5959     -0.4211     3.4830    0.2901
```
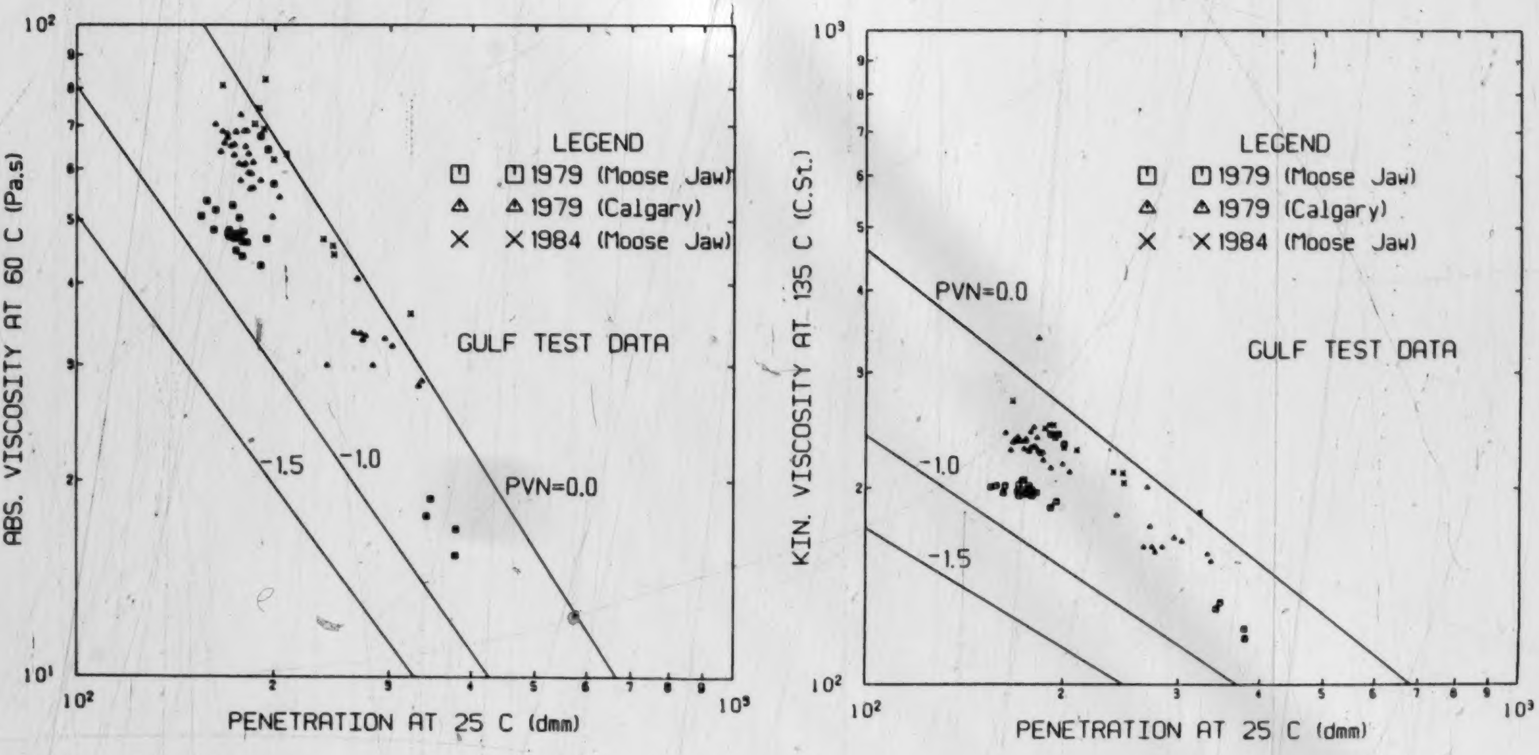

```
          SOURCE: ALL SOURCES
          GRADE  : 150/200A              YEAR : 1984
          CODE   : d-84-1

          VIS@60   VIS@135    PEN@25  %WLOSS  TVIS@60  TPEN@25    PVN@60   PVN@135    TPVN@60   RVIS@60   RPEN@25
          (PA.S) (CENTISTOKE) (DMM)    (%)    (PA.S)    (DMM)

NO. OF SAMPLES =  268      268      268    183      183      183       268       268       183       183       183
MEAN VALUE     =  80.41   265.77   166.29  0.432   203.1     91.0   -0.1539   -0.2592   -0.1860    2.5278    0.5448
ST DEVIATION   =   7.95    17.60    15.86  0.214    33.2     10.6    0.1326    0.1290    0.1154    0.4065    0.0556
CO VARIATION   =   0.10     0.07     0.10  0.497     0.16     0.12  -0.8613   -0.4978   -0.6203    0.1608    0.1020
MAX VALUE      = 114.90   315.00   323.00  1.960   348.8    125.0    0.2023    0.0269    0.3527    4.8472    0.7440
MIN VALUE      =  36.00   184.00   141.00  0.074   130.0     67.0   -0.4867   -0.7853   -0.4176    1.5682    0.3220


          SOURCE: ALL SOURCES
          GRADE  : 200/300A              YEAR : 1984
          CODE   : d-84-2

          VIS@60   VIS@135    PEN@25  %WLOSS  TVIS@60  TPEN@25    PVN@60   PVN@135    TPVN@60   RVIS@60   RPEN@25
          (PA.S) (CENTISTOKE) (DMM)    (%)    (PA.S)    (DMM)

NO. OF SAMPLES =  291      291      291    208      208      208       291       291       208       208       208
MEAN VALUE     =  43.78   199.69   251.20  0.665   113.1    128.5   -0.1072   -0.2045   -0.2389    2.5656    0.5079
ST DEVIATION   =   4.86    13.75    25.62  0.171    16.8     16.1    0.1774    0.1649    0.1874    0.2811    0.0417
CO VARIATION   =   0.11     0.07     0.10  0.257     0.15     0.14  -1.6554   -0.8062   -0.7844    0.1096    0.0821
MAX VALUE      =  66.70   287.00   353.00  1.571   200.6    175.0    0.6097    0.2919    0.1997    3.8436    0.6458
MIN VALUE      =  32.50   162.00   187.00  0.322    83.2     91.0   -0.4565   -0.4999   -0.5887    1.9620    0.3755
```

Appendix B

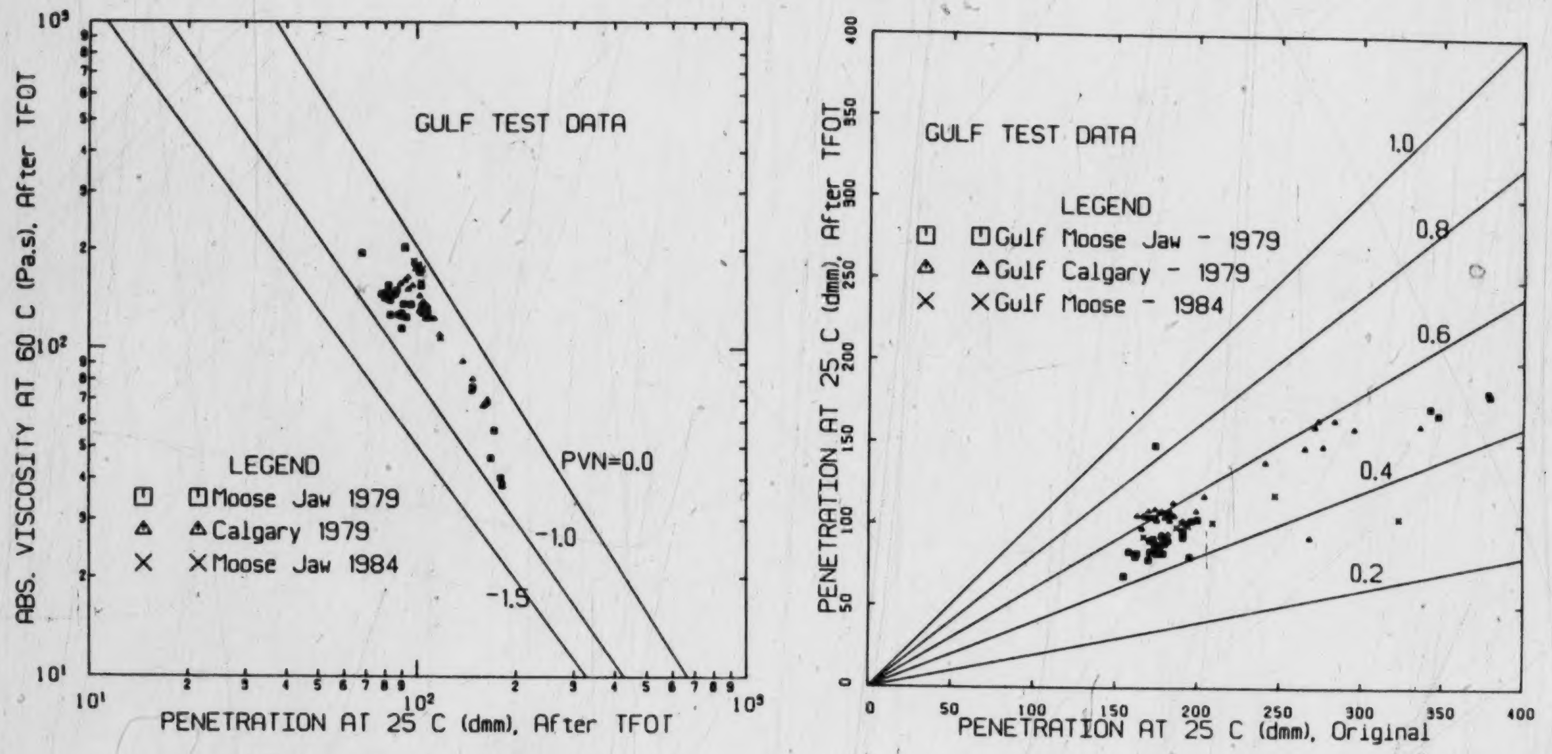
Detailed Plots of Asphalt Properties from As-supplied Test Data



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

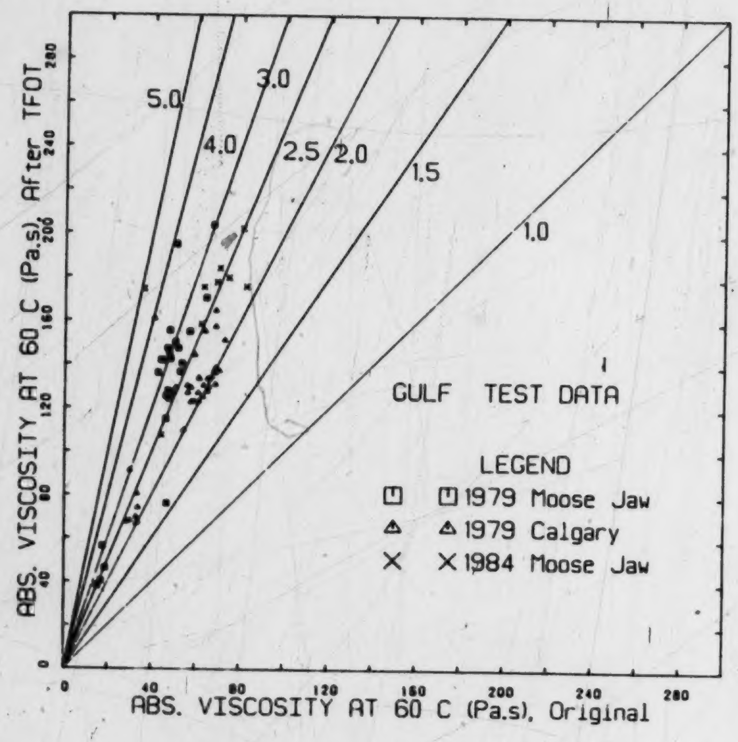
Figure B.1 Gulf 1979 and 1984 Test Data



(c) TPen 25 C versus TVis 60 C

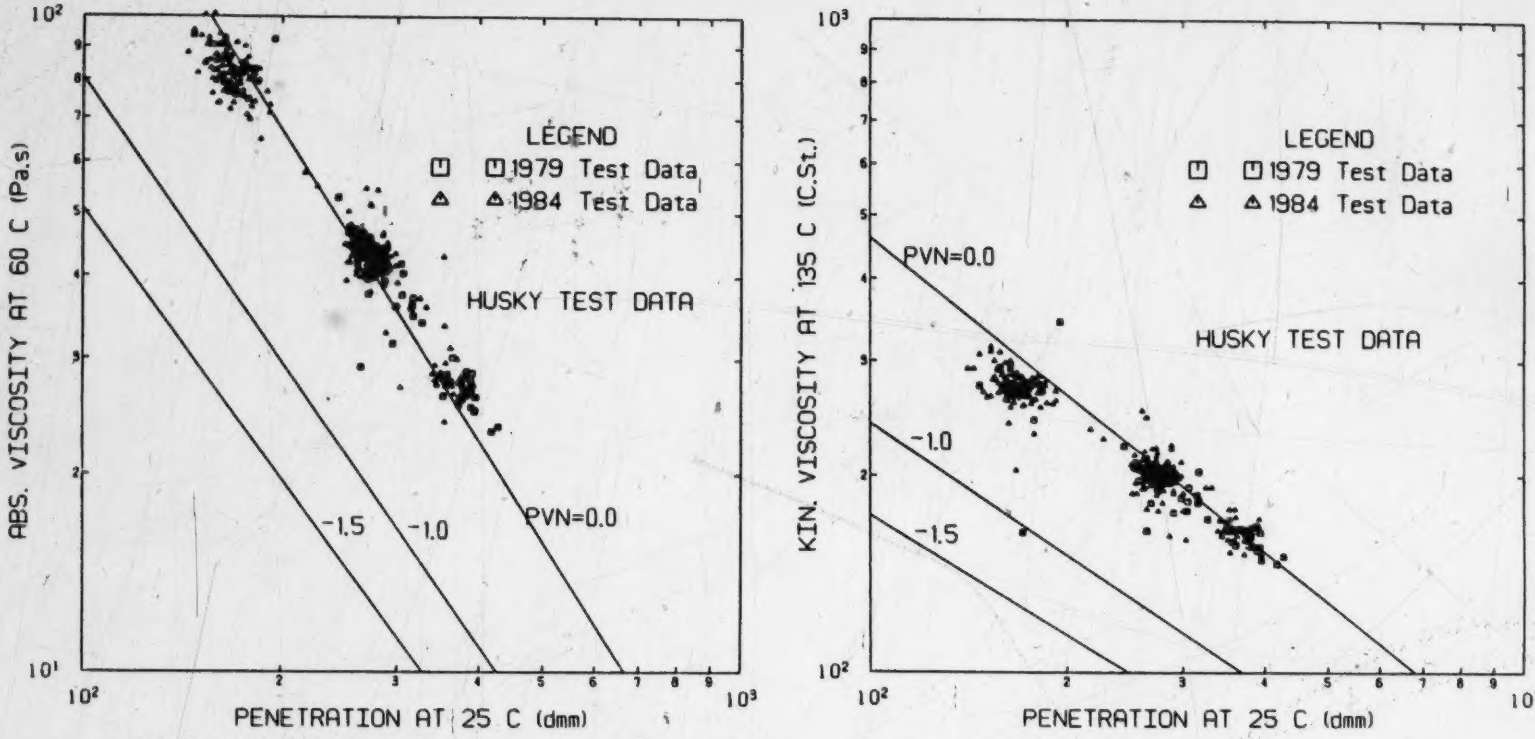
(d) Pen 25 C versus TPen 25 C

Figure B.1 Gulf 1979 and 1984 Test Data (Continued)



(e) Vis 60 C versus TVis 60 C

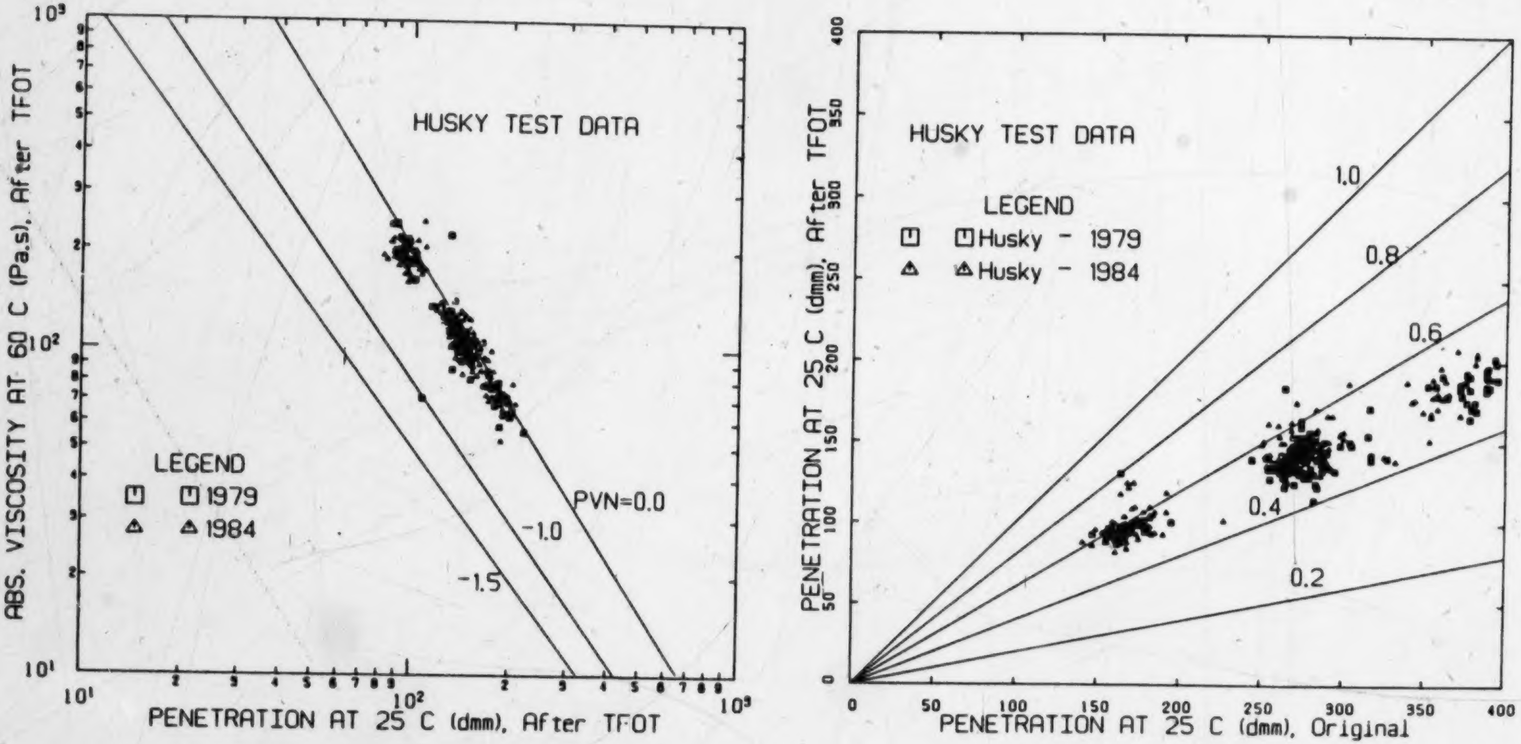
Figure B.1 Gulf 1979 and 1984 Test Data (Continued)



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

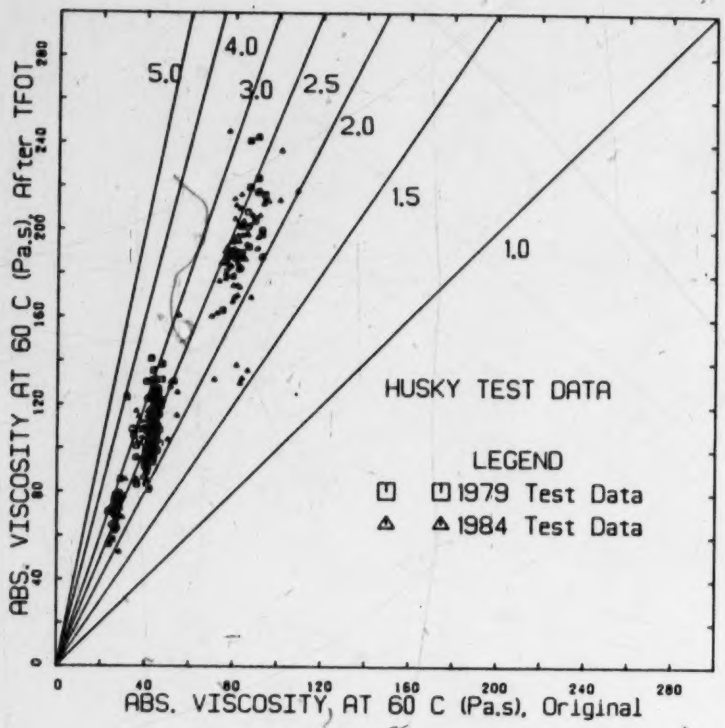
Figure B.2 Husky 1979 and 1984 Test Data



(c) TPen 25 C versus TVis 60 C

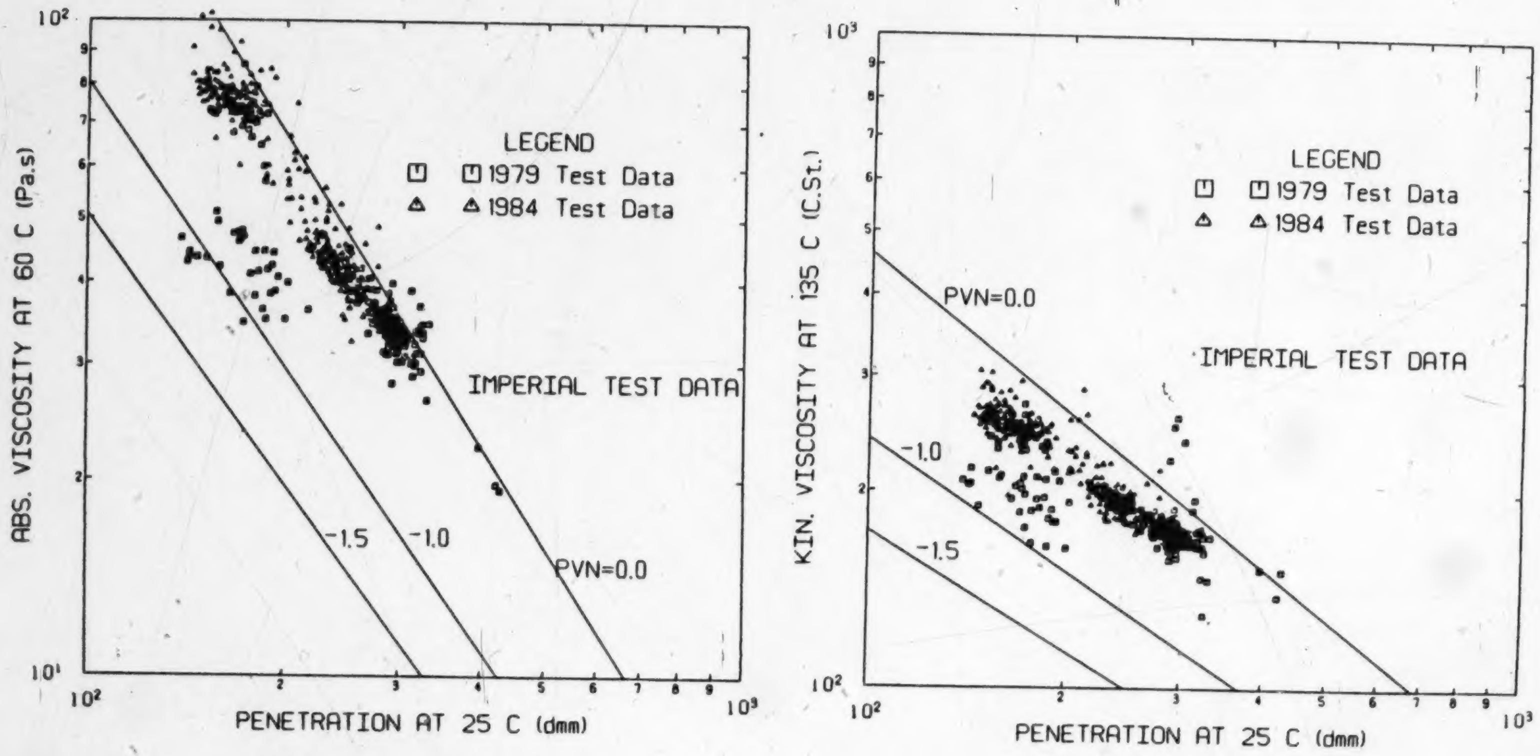
(d) Pen 25 C versus TPen 25 C

Figure B.2 Husky 1979 and 1984 Test Data (Continued)



(e) Vis 60 C versus TVis 60 C

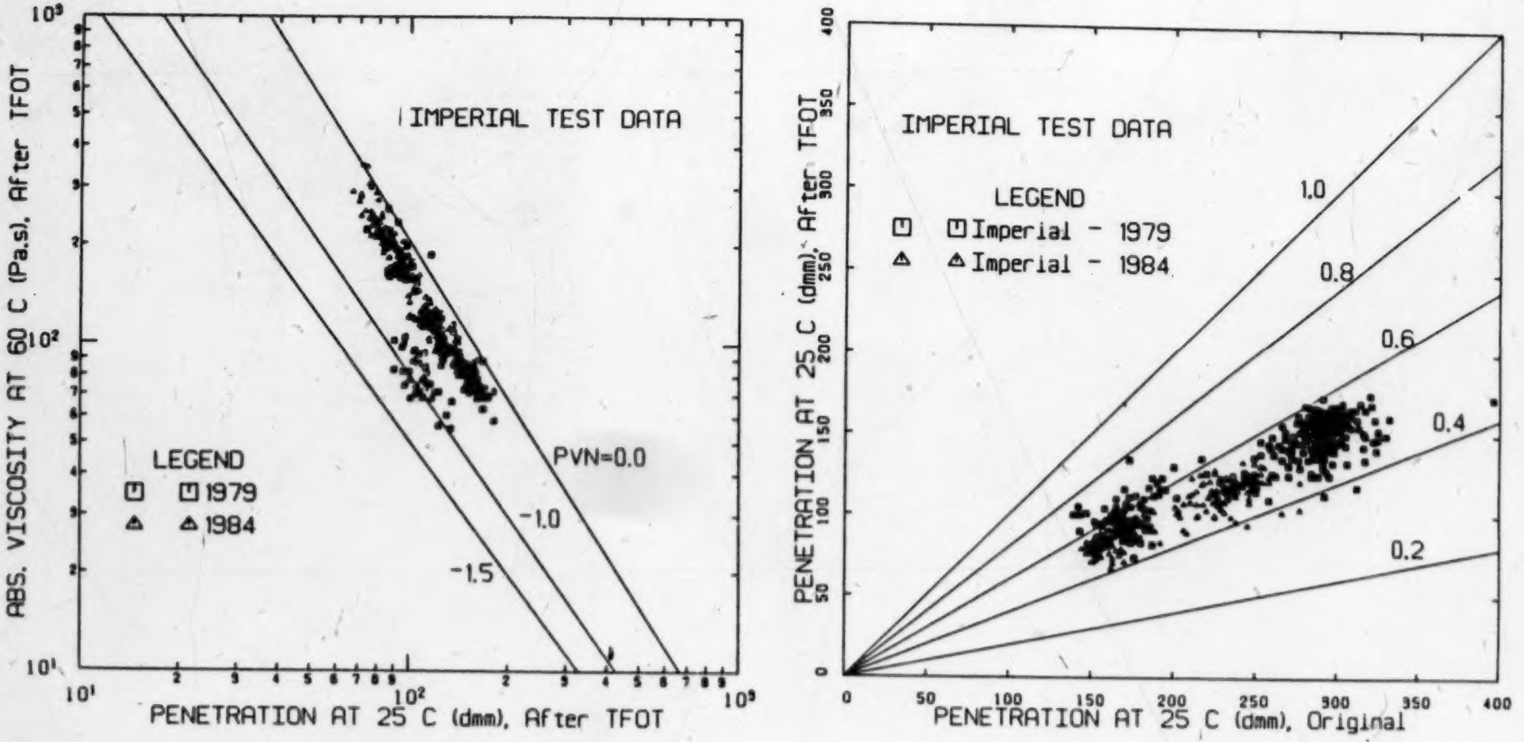
Figure B.2 Husky 1979 and 1984 Test Data (Continued)



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

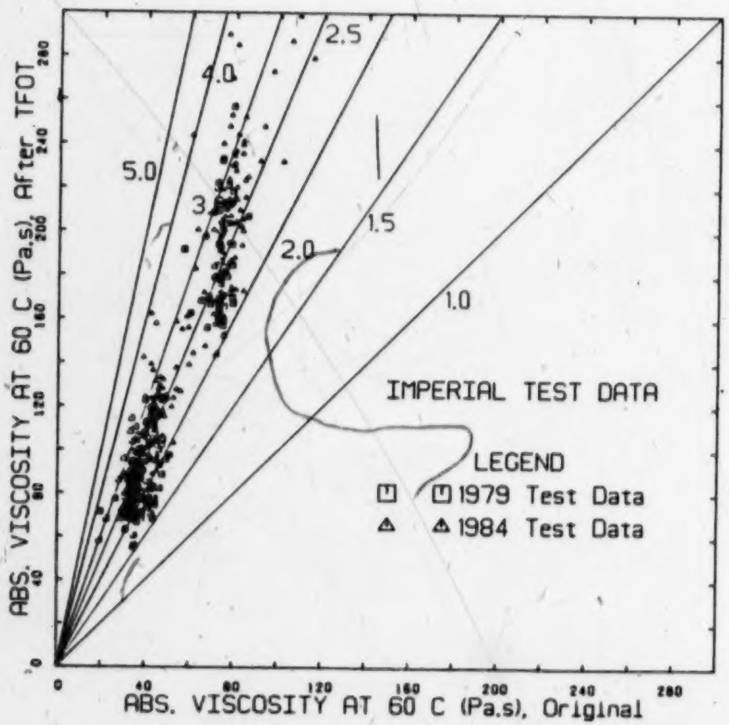
Figure B.3 Imperial 1979 and 1984 Test Data



(c) TPen 25 C versus TVis 60 C

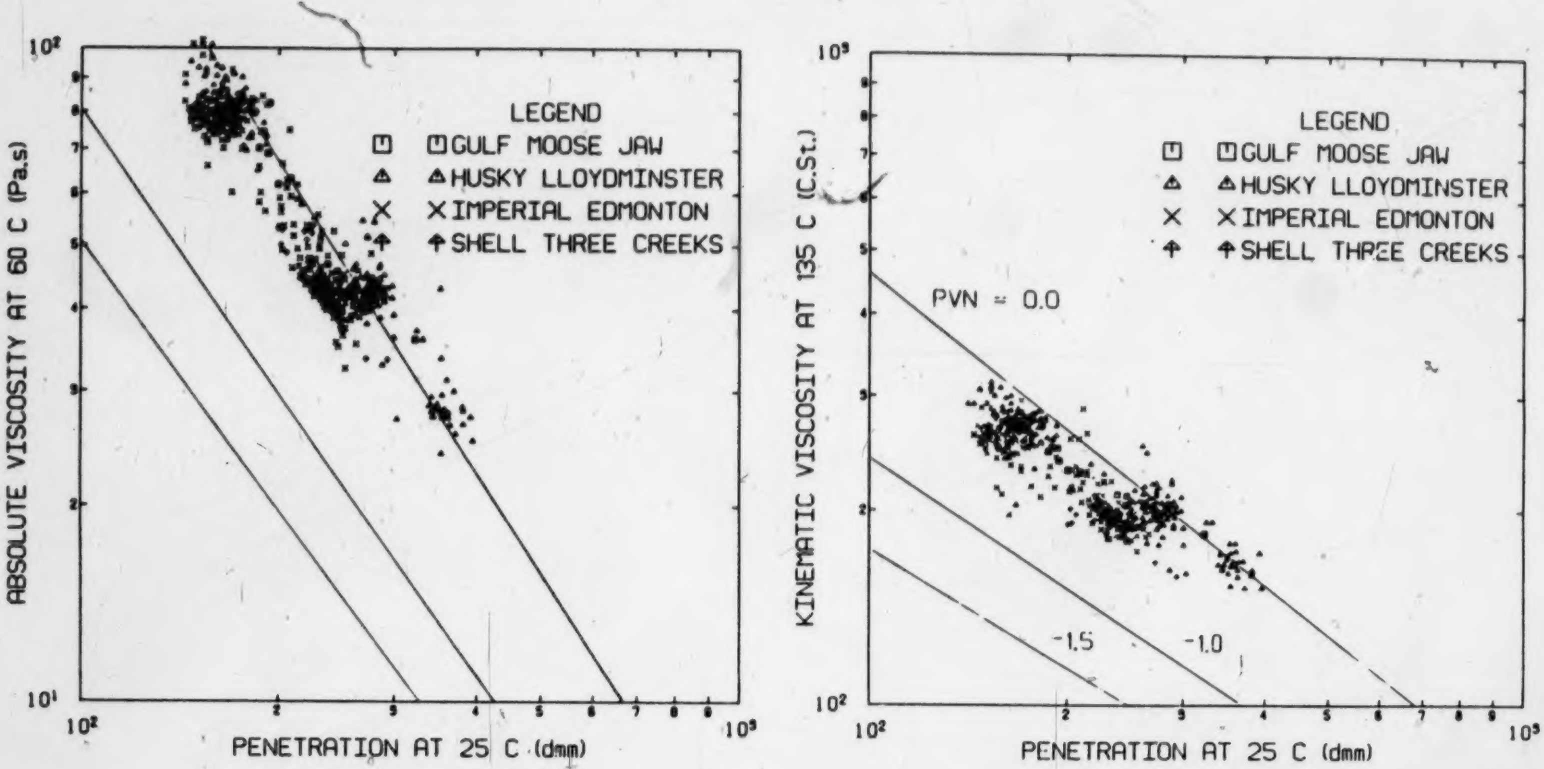
(d) Pen 25 C versus TPen 25 C

Figure B.3 Imperial 1979 and 1984 Test Data (Continued)



(e) Vis 60 C versus TVis 60 C

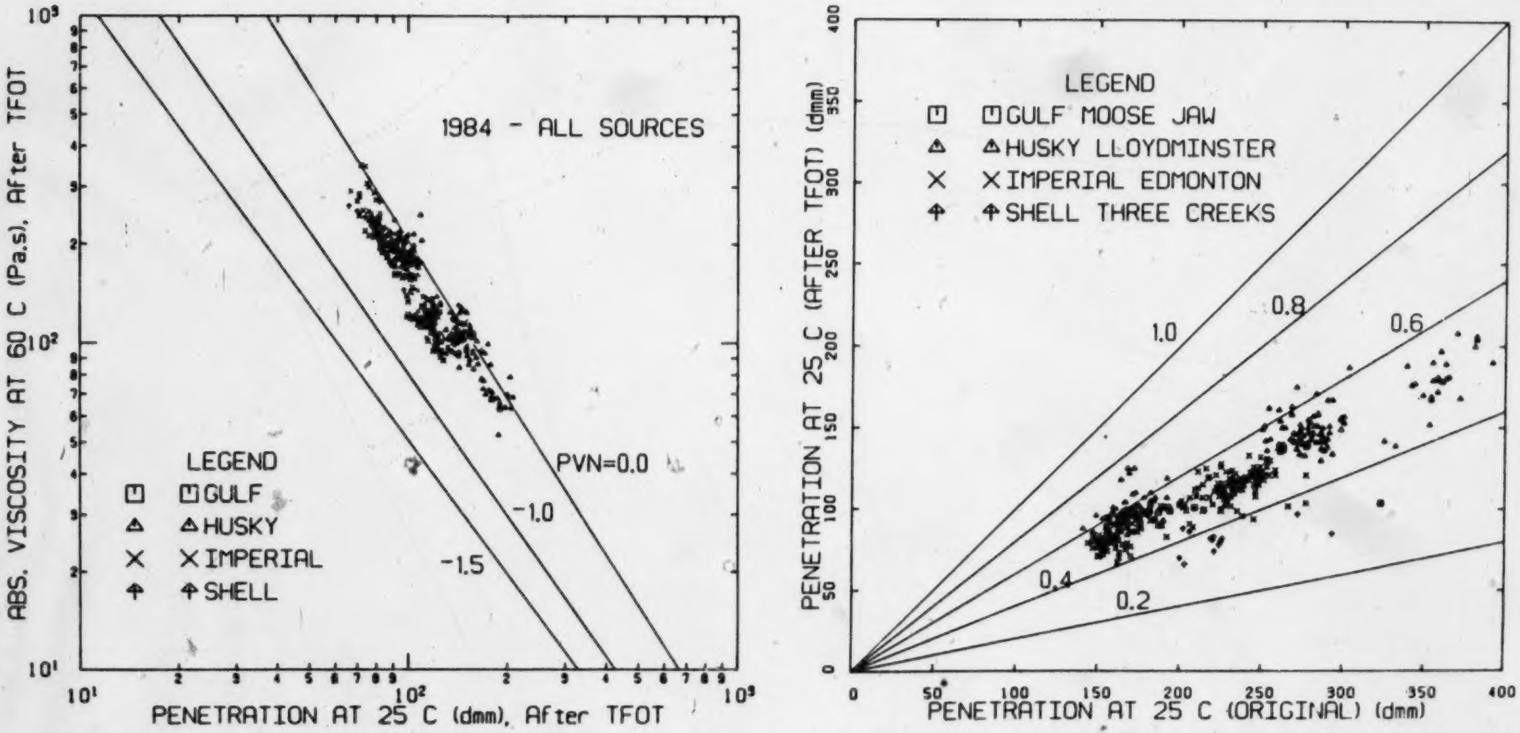
Figure B.3 Imperial 1979 and 1984 Test Data (Continued)



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

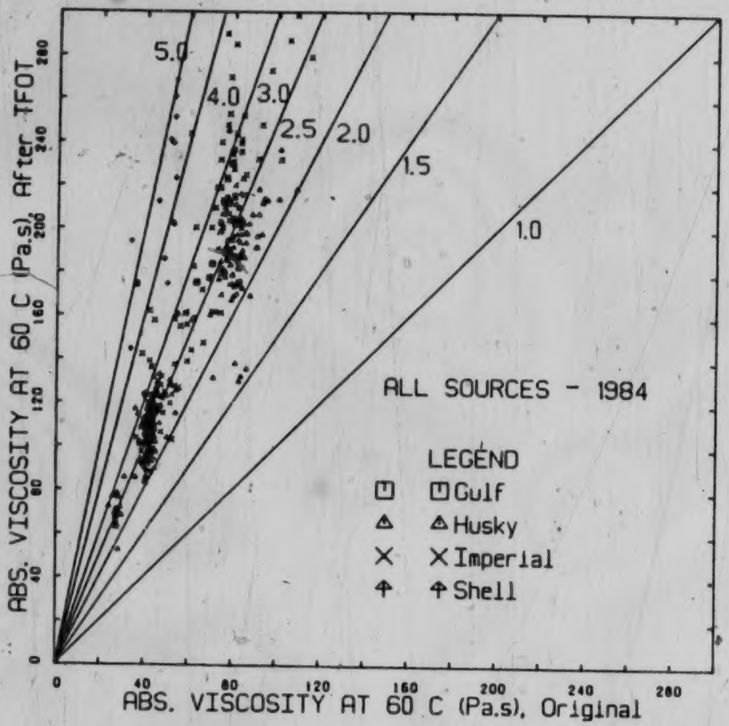
Figure B.4 1984 Test Data from All Sources



(c) TPen 25 C versus TVis 60 C

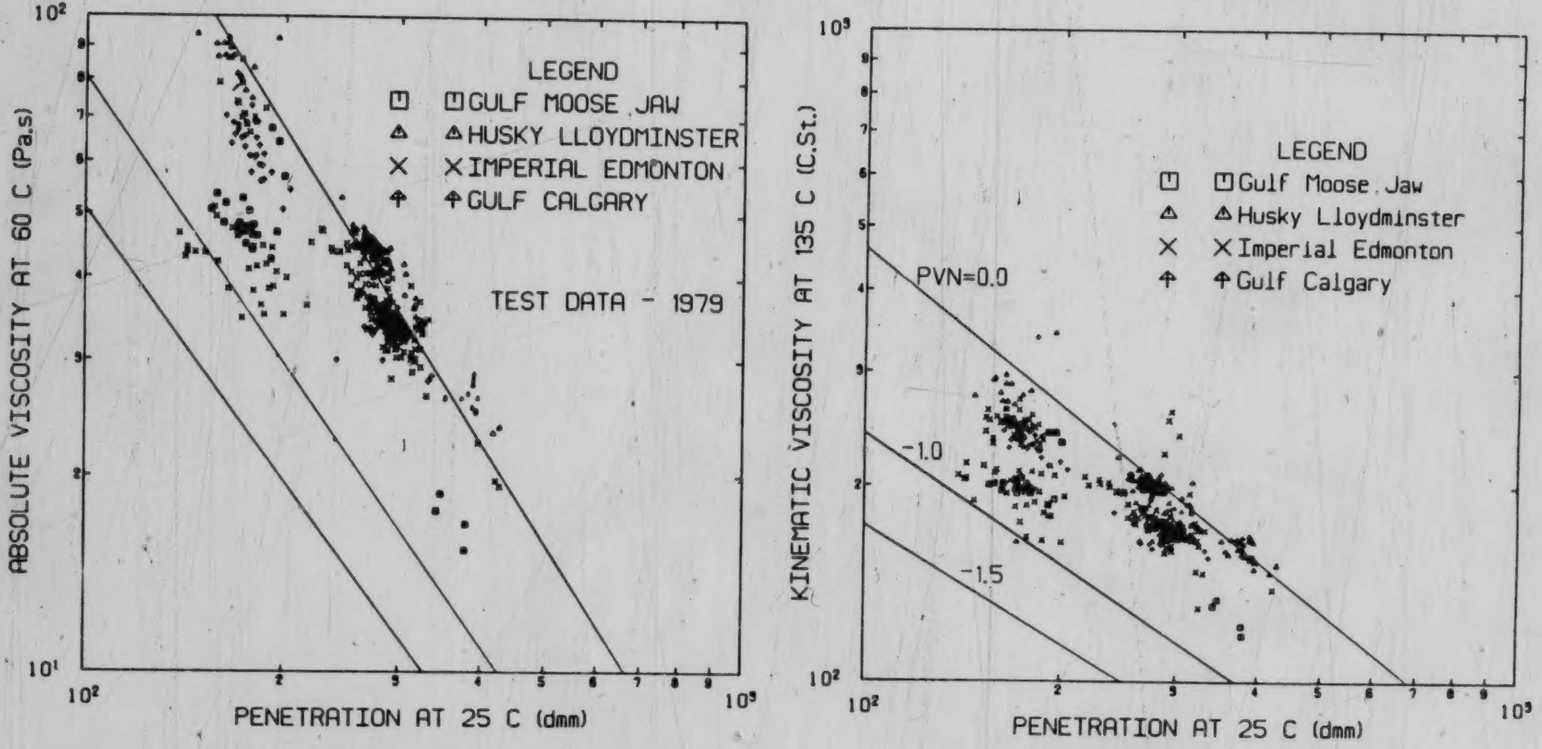
(d) Pen 25 C versus TPen 25 C

Figure B.4 1984 Test Data from All Sources (Continued)



(e) Vis 60 C versus TVis 60 C

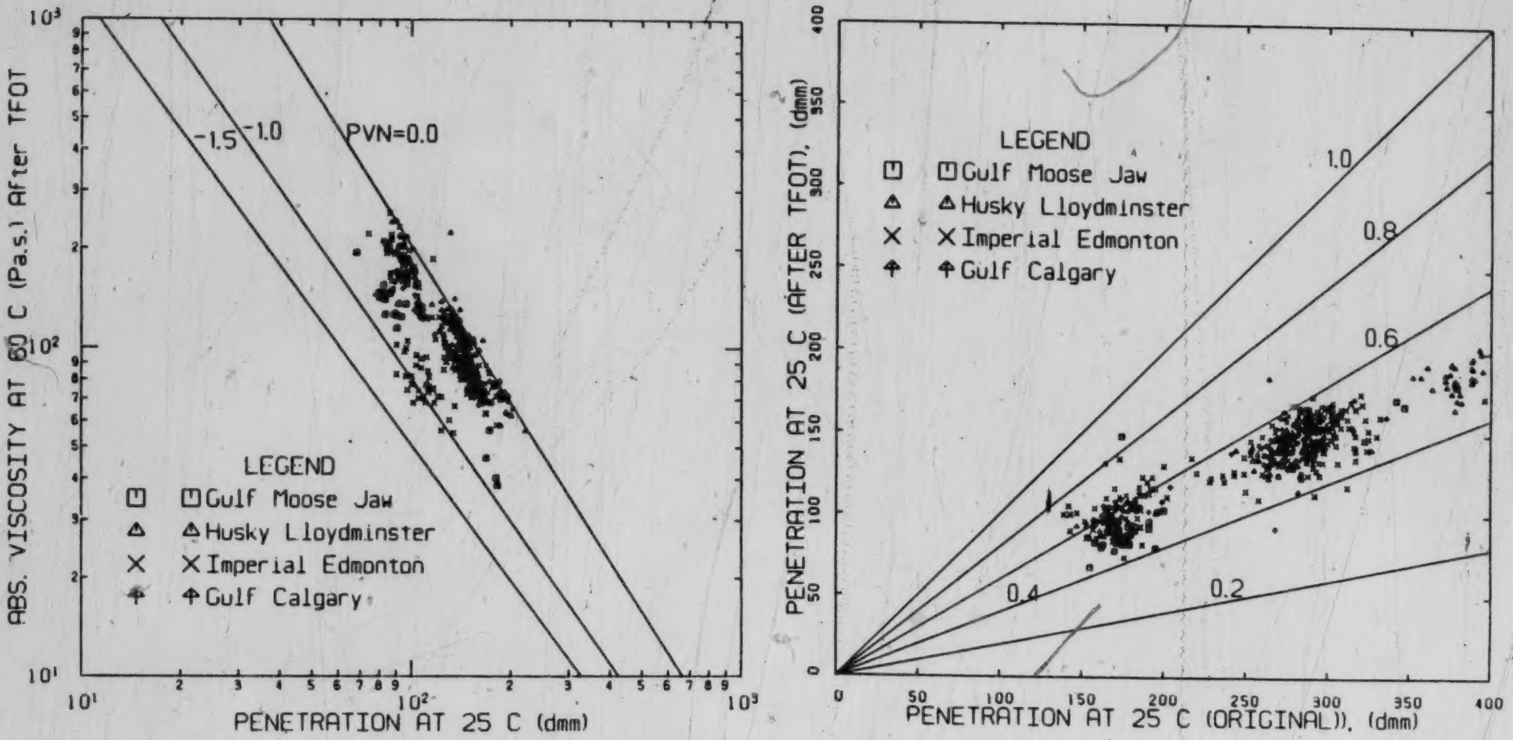
Figure B.4 1984 Test Data from All Sources (Continued)



(a) Pen 25 C versus Vis 60 C

(b) Pen 25 C versus Vis 135 C

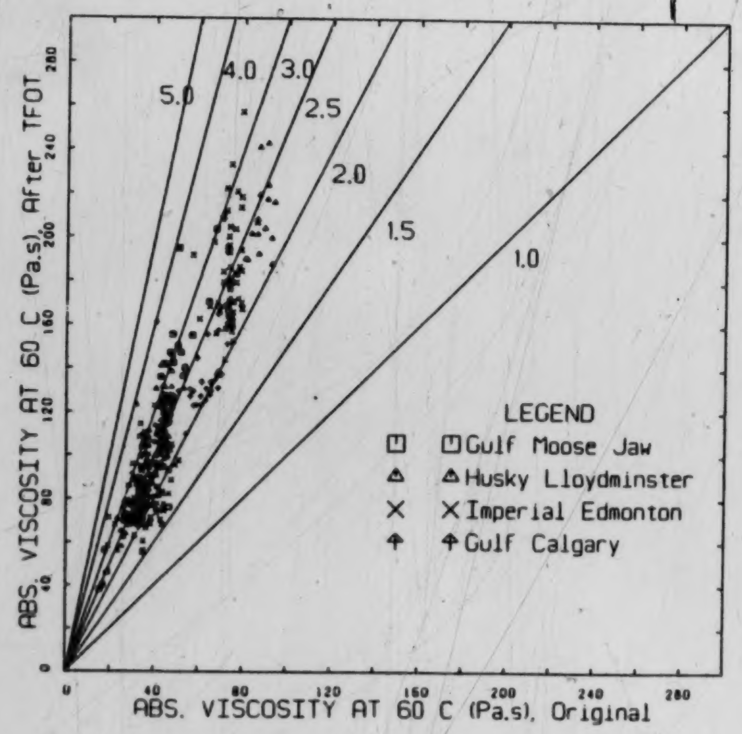
Figure B.5 1979 Test Data from All Sources



(c) TPen 25 C versus TVis 60 C

(d) Pen 25 C versus TPen 25 C

Figure B.5 1979 Test Data from All Sources (Continued)



(e) Vis 60 C versus TVis 60 C

Figure B.5 1979 Test Data from All Sources (Continued)

Appendix C

Physical Test Data of Selected Asphalt Cement Samples Provided by Suppliers

Table C1 Properties of Asphalt Cement - Supplier A

Source	Cold Lake		Redwater-Gulf Blend	
Penetration at 25°C (100/5)	96	242	93	235
10°C (100/5)	18	50	13	32
4°C (100/5)	9.0	23	6.0	13
4°C (200/60)	32.5	87.5	21.5	50
0°C (200/60)	20	55	13.5	26.5
Penetration Index[1]	-1.26	-1.01	-2.19	-2.36
Penetration Ratio[2]	33.9	36.2	23.1	21.3
Viscosity at 60°C, Pa.s	177.5	47.0	69.0	19.6
100°C, cSt	3119	1341	1220	598
135°C, cSt	371	201	178	110
Pen-Vis Number	-0.38	-0.23	-1.53	-1.39
Softening Point (D 36), °C	43.5	35.5	44.5	41.5
Ductility at 25°C (5 cm/min), cm	>150	>150	>150	105
4°C (1 cm/min), cm	>50	>50	>50	>50
Flash (COC), °C	276	252	348	334
Density at 15°C, kg/L	1.033	1.026	1.010	1.004
Thin Film Oven Test				
Change in mass, %	-0.14	-0.75	+0.12	+0.10
Residue:				
Penetration at 25°C (100/5)	61	129	60	139
Viscosity at 60°C, Pa.s	381.6	118.6	130.9	33.1
Ductility at 25°C (5 cm/min), cm	>150	>150	>150	>150
Retained Penetration, %	63.5	53.3	64.5	59.1
Viscosity Ratio at 60°C	2.15	2.52	1.90	1.69

[1] Calculated from the slope of log penetration vs temperature.

[2] $100 \left(\frac{\text{Pen } 4^{0}\text{C } (200/60)}{\text{Pen } 25^{0}\text{C } (100/5)}\right)$

Table C2 Properties of Asphalt Cement - Supplier B

Source		Lloydminster	
Product Name		85/100 Pen.	200/300 Pen.
Property	ASTM No.	Typical Analysis	Typical Analysis
Density @ 15°C, kg/L	D 70	1.0341	1.0250
Pen. @ 25°C, 100 g/5 sec.	D 5	87	257
Pen. @ 0°C, 200 g/60 sec.	D 5	21	76
Flash Point, °C	D 92	290	262
Ductility @ 25°C, cms.	D 113	150+	150+
Solubility in C_2HCl_3, 5 mass	D 2042	99.9	99.9
% Xylene for Neg. Spot Test, AASHTO	T 102	25	25
Viscosity @ 60°C, Pa.s	D 2171	196.8	47.1
Viscosity @ 135°C, mm^2/s	D 2170	418	209
Softening Point, °C	D 36	46.0	36
Salt Content, g/m^3	Husky	23	25
Thin-Film Oven Test, %loss	D 1754	0.16	0.59
Tests after T.F.O.T.:			
Pen. @ 25°C, 100 g/5 sec.	D 5	52	130
Pen. @ 0°C, 200 g/60 sec.	D 5	16	43
Vis. @ 60°C, Pa.s	D 2171	380	131
Vis. @ 135°C, mm^2/s	D 2170	558	330

Appendix D

Method of Test and Analysis for the Low Temperature Tensile Properties of Asphalt Concrete Cylinders Using the Tensile Splitting Test

D.1 Scope

This method covers the procedure developed for determining the low temperature tensile properties of asphalt concrete cylinders using the tensile splitting test. The test can be conducted on asphalt concrete laboratory specimens[2] and cored pavement specimens.

D.2 Summary of Method

The tensile splitting test method consists of loading an asphalt concrete cylinder via loading strips across a diameter, in a compression testing frame and within a controlled temperature chamber maintained at a constant low temperature. Output signals from a load cell and three linear variable differential transducers[3] are recorded on floppy diskette by means of a datalog card installed on a microcomputer. (Figure D.1)

By the use of the Lotus 1-2-3 spreadsheet program, the raw data recorded in the diskette is processed and the tensile failure stress, failure strain, failure stiffness and the stress-strain diagram can be obtained.

D.3 Significance

This method determines the tensile stress-strain and stiffness-strain characteristics of asphalt concrete at low temperatures and is primarily intended to assist in the design and evaluation of asphalt concrete with respect to thermal cracking.

D.4 Apparatus

D.4.1 Controlled Temperature Chamber

The controlled temperature chamber shall be capable of maintaining test specimens at a constant temperature ±1 °C within the range of +10 °C to -30 °C during the course of a test. A temperature monitoring device shall have its sensor embedded in a specimen of similar size and composition to the specimen which is to be tested and shall be capable of measuring temperature to ±0.5 °C.

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[2] For method of making laboratory specimens see The Standard Method of Test for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus (ASTM Designation: D 1559-82). Alternate methods for preparation of laboratory specimens may be used.

[3] Two of the LVDTs are attached to the opposite ends of the specimen and measure the horizontal deformation of the specimen. The third LVDT is placed on the loading plate and measures the vertical deformation of the specimen

D.4.2 Loading Apparatus

D.4.2.1 Compression Testing Frame

The compression frame[4] shall have a minimum capacity of 5 tons and shall be capable of providing the rate of loading prescribed in Section 6.4.1.

D.4.2.2 Supplementary Bearing Bar or Plate

The supplementary bearing bar or plate shall conform to the specifications for this item in the Standard Method of Test for Splitting Tensile Strength of Molded Concrete Cylinders (ASTM Designation: C 496-85), except that the width of the bearing bar or plate shall be not less than 33 mm.

D.4.2.3 Bearing Strips

Two steel bearing strips of dimension as shown in Figure D.2 shall be placed between specimen and both the upper and lower bearing blocks of the testing machine or between the specimens and supplemental bars or plates, if used. (See Section D.4.2.2)

D.4.2.4 Load Cell

The load cell[5] shall have a minimum capacity of 4.5 tonnes and shall be capable of measuring compressive loading to ±1 per cent of true at the rate of loading prescribed in Section 6.4.1.

D.4.3 Gauge Points, and Marking and Mounting Apparatus

D.4.3.1 Gauge Points

The gauge points shall be 9.525 x 9.525 x 6.35 mm (0.025 mm from mean in any dimension) brass plates.

D.4.3.2 Gauge Point Jig

The gauge point jig shall provide slots for marking the specimen and holes for mounting the Gauge Points. (Figure D.3)

D.4.4 Deformation Measurement Apparatus

D.4.4.1 Horizontal Displacement Gauges

The displacement gauges[6] shall be two linear variable differential transducers of matched sensitivity (within 5%) and be capable of measuring displacements to within ±0.00125 mm, and shall have a stroke of not less than ±0.25 mm.

---

[4] A suitable device (Wykeham Farrance Mod. 57, 5 ton compression tester) may be obtained from Wykeham Farrance Engineering Ltd., 127 Edinburgh Avenue, Slough, Bucks, U.K.

[5] A suitable device (Kwoya Musen Load Cell Mod. LC-5,5 ton) may be obtained from Kwoya Musen Kenkyujo Co., Ltd., Tokyo, Japan.

[6] Suitable devices (Sanborn Linear Variable Differential Transformers Mod. 595 DT 025) may be obtained from the

D.4.4.2 Displacement Gauge Core and Coil Assemblies

The two displacement gauge core and coil assemblies which hold the Horizontal Displacement Gauges shall be made of brass (Figure D.4)

D.4.4.3 Vertical Deformation Gauge

The displacement gauge[7] shall be a linear variable differential transducer capable of measuring displacment to within 0.01 mm. The gauge shall be mounted on the compression frame and measures the movement of the loading plate.

D.4.4.4 Displacement Gauge Calibration Jig

The displacement gauge calibration jig shall be made of brass and aluminum (Figure D.5) The dial gauge which comprises a portion of the displacement gauge calibration jig shall be a 0.0025 mm dial gauge.

D.4.5 Data Acquisition Apparatus

D.4.5.1 Computer Hardware

The computer hardware[8] for acquiring and recording test data consists of the following:

30. *A microcomputer system* with minimum 512K Ram is required although 640K Ram is prefered in order to provide a margin of safety for the computer operation.
31. *Two double sided, double density disk drives* are required in order to run the softwares. The first or 'A' drive contains the operating system and the BASIC program. The second or 'B' drive is used to stor test data upon completion of the test.
32. *A multifunction card* is used for printer communication.
33. *A clock card* is used to note the time.
34. *A Metra Byte Dash-8 Board*[9] is used to collect the test data in anolog form and convert them into digital form for use by the computer. The Dash-8 board has 8 channels available for datalogging. Only five is needed. They are:
    a. Channel 0 ----- Load Cell
    b. Channel 1 ----- LVDT A
    c. Channel 2 ----- LVDT B

---

[6] (cont'd) Sanborn Co., 175 Wyman Street, Waltham 54, Massachusetts, USA.

[7] A suitable device may be obtained from Hewett Packard

[8] A suitable microcomputer, an IBM PC clone, can be obtained from Operand Electonics Ltd. of Edmonton.

[9] The Dash-8 board is manufactured by the Metra Byte Corp

d. Channel 3 ----- Average of A and B
e. Channel 4 ----- Vertical LVDT

The Dash-8 board has a full scale input of + 5 volts on each channel with a resolution of 0.00244 volt.

D.4.5.2 Computer Software

Two software packages are required by the computer to acquire and record the test data. One is the IBM PC DOS version 3.1 and the other is the Dash-8 configuration package. A BASIC program written specifically for the tensile splitting test is also required.

The DOS'* disk operating system allows the establishment of a virtual disk on the computer for temporary data storage. When the test is finished, the contents of the virtual disk is transferred to the 'B' drive.

The Dash-8 software package'' provides the input output driver routine which can be accessed from BASIC using the Call statement.

The BASIC program defines various functions and operation in the use of the computer hardwares. The main function and operation defined in this program include the gathering of test data at designated intervals and duration; and the storing of the data in the computer and copying them to drive 'B', by using the Dash-8 software package. A listing of this program is enclosed in Section D.10.

D.4.5.3 Signal Conditioner

The signal conditioner is used to amplify, filter and condition the input signals from the test before sending the signals to the Dash-8 board.

The conditioner also serially connects the input signals of the LVDT A and LVDT B resulting an average value for the horizontal deformation.

In addition to the above functions, the conditioner is used to zero the signals of the load cell and the LVDTs, before sending them to the Dash-8 board.

D.5 Test Specimens

D.5.1 Asphalt Concrete Laboratory Specimens

If Marshall specimens are to be tested they shall conform to the specifications set forth in ASTM Method D 1559-76.

'* For details of the software plus technical information, refer to the DOS 3.1 manual.

'' For details of the software plus technical information, refer to the Dash-8 manual.

D.5.2 Asphalt Concrete Cored Pavement Specimens

If cored pavement specimens are to be tested they shall be trimmed to a cylindrical shape (within ±0.25 mm of the mean length and diameter) having a diameter of 102 mm, ±2.5 mm and a length of less than 102 mm.

D.6 Procedures

D.6.1 Calibration

D.6.1.1 Load Cell

The Load Cell shall be calibrated at room temperature (if temperature compensating) or at the test temperature (if non-temperature compensating), on a Compression Tester whose load accuracy has been verified to + 1 percent in accordance with the Standard Methods of Verification of Testing Machines, ASTM Designation: E4-64.

D.6.2 Dial Gauge

The dial gauge shall be calibrated while on the Displacement Gauge Calibration Jig described in Section D.4.4.4, using machinist's gauge blocks.

D.6.2.1 Displacement Gauges

The two horizontal displacement gauges shall be calibrated when the two gauges are connected in series. They shall also be calibrated separately. The calibration shall be carried out on the Displacement Calibration Jig (using a 25.4 mm gauge length at null) at the test temperature. Output signal (in terms of voltage) from the displacement gauges shall be measured by a digital voltmeter as well as by the computer data acquisition system.

D.6.3 Preparation of Specimen for Testing

D.6.3.1 Measurement

Determine the length and diameter of the test specimen to the nearest 0.25 mm by averaging four readings at each dimension.

D.6.3.2 Marking

Mark dimetral loading points on each end of the specimen in the same axial plane using the Gauge Point Jig described in Section D.4.3.2.

D.6.3.3 Gauge Point Attachment

Cool the specimens to at least -10 °C for about 2 hours before attaching the gauge points. Coat one side of each of two gauge points (described in Section D.4.3.1.) with warm asphalt cement. (Use grade 200/300A asphalt cement for testing at temperature of -10 °C or below. Use grade 85/100A asphalt cement for testing at temperature above -10 °C.) Warm the gauge points and insert the two coated Gauge Points through the holes in the aligned Gauge Point Jig and press firmly onto the specimen. Leave the specimen to cool horizontally for approximately 3 minutes to firmly affix the gauge points to the specimen. Invert the specimen (and prop in a manner that will not disturb the previously attached Gauge Points) and attach the other two Gauge Points in a similar manner.

D.6.3.4 Cooling

Immediately place the specimen into the Controlled Temperature Chamber.

D.6.4 Preparation for Loading of the Specimen

D.6.4.1 Specimen Inspection

After the specimen to be tested has reached equilibrium temperature, inspect it for Gauge Point slippage. If any slippage is evident remove the Gauge Points and repeat steps D.6.2.3 and D.6.2.4.

D.6.4.2 Positioning

Place the Load Cell on the loading ram platen of the Compression Testing Frame. Position the specimen so that the marked loading points are in a vertical plane passing through the center of thrust and so that the longitudinal axes of the Bearing Strips are in this vertical plane. Raise the loading ram of the Compression Testing Frame just enough to secure the specimen for Displacement Gauge attachment.

D.6.4.3 Displacement Gauge Attachment

Tie both of the Displacement Gauge Core and Coil Assemblies to some point on the Compression Testing Frame to obviate damage after specimen failure. Simultaneously place the rear Displacement Gauge Core and Coil Assembly onto the Gauge Points and then secure the assemblies by tightening the allen screws. Repeat the foregoing attachment procedure for the front Displacement Gauge Core and Coil Assembly.

D.6.5 Loading and Recording Procedure

D.6.5.1 Loading Rate

Set the Compression Testing Frame to a nominal loading rate of 1.5 mm/min. The actual loading rate may vary from the nominal loading rate by ±10 percent but must be reproductible within ±1 percent.

D.6.5.2 Loading

Engage the Compression Testing Frame and return to the recording area (Note: Loading will not begin until the power supply switch for the servo motor is closed. This switch should be located in the recording area, adjacent to the recorder).

D.6.5.3 Recording

Make sure all the wirings are hooked up correctly. Adjust the signal conditioner switches such that the voltage outputs from the load cell and the displacement gauges to the datalog card are conditioned close to ±0.000 V. Run the computer program for datalogging. Input information as requested from the screen. This include the duration of recording data, the frequency of reading data and the name of channels to be used. (Channel 0 to Channel 4) The name of the sample will also be requested and will be used as the filename of the dataset. Press the run key and the computer will start to record data.

Record all other pertinent data such as date of test and test temperature (air and specimen) on the laboratory log book.

The computer will stop recording data after the given period of time and copy the data set into floppy diskette.

D.6.5.4 Termination of Test

Upon failure of the specimen, turn off the power supply switch for the servo motor. Disengage the Compression Testing Frame and examine the fractured specimen. If the fracture surface passes under a Gauge Point the test shall be rejected.

D.7 Calculations

D.7.1 Tensile Stress

The tensile stress at any point to failure shall be calculated as follows:

$$T = \frac{2 * P}{\pi * t * d}$$

where:

t = specimen thickness, in m

d = specimen diameter, in m

T = tensile stress, in KPa

P = applied load, in KN, calculated as follows:

$$P = \frac{N_p * k_1}{410}$$

where:

N_p = values, in binary bit form as recorded in channel 0 of the data file, 1 volt = 410 bits,
k_1 = conversion factor of load cell, in kilonewton per volt obtained from calibration.

D.7.2 Strain

The strain, at any point to failure is equal to the average deformation, in mm, as measured by the two horizontal deformation gauges, A and B, calculated as follows:

$$\epsilon = \frac{N_{ab} * k_2}{410 * 25.4}$$

where:

ϵ = average deformation of the strain gauges A and B, in mm/mm
N_{ab} = value as recorded in binary bit form in channel 3 of the data file, 1 volt = 410 bits,
k_2 = conversion factor of the deformation gauges in mm per volt.

Due to the biaxial state of stress existing within the cylindrical specimen, the displacement measured between the gauge points is a result of both compressive stresses in the vertical direction and tensile stresses in the horizontal direction. The term strain is used without differentiation as to its cause. If tensile strain is desired, as for calculation of a stiffness modulus, use of equations applying the Generalized Hooke's Law is necessary.

D.7.3 Failure Strain

The failure strain shall be considered as the strain corresponding to the first maximum stress reach during the test.

D.7.4 Tensile Strength

The tensile strength shall be considered as the maximum tensile stress.

D.7.5 Stiffness Modulus

The tensile stiffness modulus at any point to failure shall be calculated as follows:

$$S_t = \frac{0.912 * T}{0.5 * \epsilon_{ab}}$$

where:
S_t = Tensile Stiffness Modulus in MPa,
T = tensile stress in MPa,
ϵ_{ab} = average strain of strain gauges A and B in mm/mm.

D.7.6 Data Processing

When the test is terminated, the raw test data stored in the disk is processed by an IBM XT microcomputer[12] using the Lotus 1-2-3 spreadsheet program. A lotus 1-2-3 Macro program is written specifically to perform the calculations which are described earlier in this chapter. A listing of the Macro program and the instruction for using it are contained in Section D.10.

The printout of the processed data includes the stress, strain and stiffness of the specimen at each point of time during the test. The failure stress, failure strain and failure stiffness are determined by locating the maximum stress the specimen has first experienced. A sample printout is contained in Section D.10.

By selecting the appropriate pairs of stress-strain data, the stress strain diagram of the test specimen can be drawn by means of the Lotus 1-2-3 graph software or any other plotting programs.

D.8 Report

The report shall include the following:

1. Identification number, aggregate identification, asphalt cement penetration or viscosity, and asphalt cement supply,
2. Test temperature,
3. Rate of loading
4. Specimen diameter, and thickness,
5. A printout of the processed data of stress, strain and stiffness,
6. The failure strain,
7. The tensile strength,
8. A stress-strain diagram, and
9. Any abnormalities in the type of fracture.

---

[12]. The data can also be processed with other IBM PC with slightly modified procedures.

D.9 Sources of Experimental Errors

The following are some of the sources of experimental errors that have been identified in the tensile splitting test method described in the previous chapters. Possible procedures to reduce these errors are also presented.

1. Shape of specimen may not be truly cylindrical. This may be caused by distortion during extraction in the case of Marshall briquette or by poor quality coring in the field. This error will cause non-uniform loading of the specimen leading to erroneous results. To reduce this error, strict adherence to ASTM D-1559-82 for preparation of Marshall briquettes and well supervised coring in the field are necessary.
2. The level of the loading platens of the compression machine may not be truly horizontal. This again will result in non-uniform loading of the specimen. To ensure that the loading platens are level, check and adjust the loading platens before each test.
3. The loading strips may be seated improperly. This will result in loading the specimen not in an axial plane which is assumed in the theory to calculate the stress distribution. To avoid this error to happen, align the diametral lines of the specimen with the centre of the loading strip and the line of thrust of the testing machine.
4. The compression machine may vibrate excessively, particularly at the start of a day's testing and/or at colder temperature. This will result in a large fluctuation of the readings of the LVDTs. To eliminate this problem, run the machine for a few minutes before starting the day's tests. Also check to ensure the driving belt of the servo motor is tight.
5. The reading of the LVDTs may be moving before the test begins. (very often at higher temperature) This indicates that either the LVDTs are not secured to the gauge points or the gauge points are slipping. To overcome this problem, tighten the allen screws of the core and coil assemblies and check the slippage of the gauge points. If slippage of the gauge points is identified, remove the gauge points and re-attach the gauage points using a harder asphalt. (Section 6.2.3)
6. The LVDTs may not at a horizontal position. This will result in inaccuracy in the strain reading. The problem may be caused by gauge point slippage, inaccuracy in marking the diametral lines or improper positioning of the specimen. To overcome this problem, check the position of the specimen and the accuracy of the diametral lines. Check the slippage of the gauge point. Make sure that the gauge points are firmly affixed (that is, the asphalt cement is cool) before inverting the specimen for another pair of gauge point.
7. The air temperature of the cold chamber may fluctuate, very often as much as 2 to 3 C during the course of the test. The temperature of the specimen also fluctuates,

but to a lesser extent in the order of 1 to 2 C. This fluctuation is caused by heat loss when opening the door of the cold chamber and the sensitivity of the thermostat which controls the activation of the compressor of the cold chamber. In general, provided the door of the cold chamber is closed tightly every time a person enters or leaves the chamber, a couple of adjustments of the thermostat is sufficient to bring the temperature of the specimen to within 1 C of the required test temperature.

8. The temperature of the cold chamber may be increasing though the thermostat is kept at the same temperature. This happens very often after a long duration of colder temperature being kept in the cold chamber because frost has been developed. To solve this problem, a half hour defrost operation is neccessary.
9. The readings of a particular channel may stay constant at +2048. This happens when the input signal into the computer is exceeding +5V which is the extremes that the datalog card can read. This problem may be caused by either the LVDTs are not within their stroke range (for example, the gauge points are not at a distance of 25.4 mm apart) or the signal conditioner is not used to condition the signal close to zero before starting test. To eliminate this problem, check that the LVDTs are positioned within their stroke range and that the signal conditioner is used to condition the signal to close to zero volt with a voltmeter.

D.10 Listing of Computer Programs and Sample Printout

D.10.1 BASIC Program for Data Acquisition using the DASH-8 Card

```
120 OPEN "dash8.adr" FOR INPUT AS #1
130 INPUT #1, BASADR%
135 CLOSE #1
136 CLS
200 DIM DIO%(8),LT%(2)
210 INPUT "Enter length of stage #1(1 to 60 min.)";S1
220 INPUT "Enter interval(1 to 60 sec)";I1
230 INPUT "Enter length of stage #2(1 to 60 min.)";S2
240 INPUT "Enter interval(1 to 60 sec)";I2
250 TCOUNT=(S1*(60/I1))+(S2*(60/I2))
260 INPUT "Enter first channel";FC%
270 INPUT "Enter last channel";LC%
275 MD%=1:LT%(0)=FC%:LT%(1)=LC%:CALL DASH8 (MD%, LT%(0), FLAG%)
280 INPUT "Enter file name";F$:FF$="c:"+F$+".prn"
290 OPEN FF$ FOR OUTPUT AS 3
400 MD%=0:CALL DASH8 (MD%, BASADR%, FLAG%)
450 'enter stage #1
465 ON TIMER(I1) GOSUB 4000
470 ON KEY(1) GOSUB 2000:ON KEY(2) GOSUB 2500
480 KEY(1) ON:KEY(2) ON
485 PRINT"Press F1 to start test"
500 IF TEST=1 THEN GOTO 3000
510 GOTO 500
2000 TEST=1:RETURN
2500 OF=1:RETURN
3000 TIMER ON 'start datalogging
3010 IF OF=1 THEN GOTO 5000
3020 GOTO 3010
4000 IF READNO.=TCOUNT THEN GOTO 5000
4001 IF READNO.=S1*(60/I1) THEN ON TIMER(I2) GOSUB 4000
4003 MD%=2:CH%=FC%:CALL DASH8 (MD%, CH%, FLAG%)
4005 FOR I=FC% TO LC% 'a/d routine
4020 MD%=4:CALL DASH8 (MD%, DIO%(I), FLAG%):NEXT I
4030 READNO.=READNO.+1:TC=VAL(LEFT$(TIME$,2)+MID$(TIME$,4,2)+RIGHT$
4040 PRINT TC READNO.;:FOR I=FC% TO LC%:PRINT DIO%(I);:NEXT I:PRINT
4050 PRINT #3,TC READNO.;:FOR I=FC% TO LC%:PRINT #3,DIO%(I);:NEXT I
4060 RETURN
5000 CLOSE 3:SYSTEM
```

D.10.2 Lotus 1-2-3 Macro Program for Data Processing

The following is a listing of the LOTUS Macro that is used to perform the necessary calculations on the data from the tensile splitting tests. Along with the macro are included some comments to aid in future modifications of the macro. These comments DO NOT appear on the worksheet. The macro does not appear here in the same format as on the worksheet in order to facilitate the inclusion of comments.

This is the main macro which controls the selection of files to be processed. The files are to be listed under the headings of: "SAMPLE" and "TEMP" and "THICK". Under the "SAMPLE" heading input the name of the file that contains the test data. The "TEMP" requires the input of the temperature at which the sample was tested. The "THICK"ness is to be input in millimeters.

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```
{goto}BEGIN¬     | this section         SAMPLE       TEMP    THICK
/rndIDA¬         | initializes
/rndTEMP¬        |  the macro           RW20          -20     69.6
/rndTHIK¬        |                      H12           -30     69.7
/rncIDA¬¬
{goto}IDA¬
/rndIDA¬
{down}
/rncIDA¬¬
{right}
/rncTEMP¬¬
{right}
/rncTHIK¬¬
/xiTHIK=0¬/xq¬
/cIDA¬
SAMNO¬
/cIDA¬            | this section copies the data
SAMNO2¬           | to other portions of the wks for
/cIDA¬            | subsequent use by the following macros
FRET¬             |
/cTEMP¬           |
SPTEMP¬           |
/cTHIK¬           |
THICK¬            |
/xcSTART¬         | this transfers control to the "START-UP" macro
/rndTEMP¬
/rndTHIK¬
/xgLOOP4¬         | this loops the macro back to the first line


START-UP MACRO

/wgrm             | set the wks recalc to manual
/reALL¬           | erase old data
/rncTEST2¬¬
/rncTEST3¬¬
/rndTEST2¬
/rndTEST3¬
{goto}A5¬
/finUSR\GARYV\TENSILE\              | importing the data file
H12
0{goto}TABLE1¬
/c¬C250..J250¬                      | initializing the first value to
{goto}TABLE2¬                       | approx. zero (0) on calc table
(@ABS(C6-$C$5)+1.0000E-11)
/410*1000¬                          | calculations to convert the imported
{right}                             | data (bit format) into SI form of data
(@ABS(D6-$D$5)+1.0000E-11)  A       | ie. deflections, loads etc.
/410*0.01¬
{right}
(@ABS(E6-$E$5)+1.0000E-11)  B
/410*0.01¬
```

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```
{right}
(@ABS(F6-$F$5)+1.0000E-11)  A+B
/410*0.0156¬
{right}
(@ABS(G6-$G$5)+1.0000E-11)  LVDT VERT
/410*3.9267¬
([illegible]204*2/                         | calculating the stress on the sample
(@PI*($THICK/25.4)*4))*6.89476¬
{goto}STRATE¬                              | calculating the strain rate
(G251-G250)*60¬
{goto}SISTIFF¬                             | calculating the sample stiffness
(0.912*H251/(0.5*F251))/1000¬
/cA5..B240¬
A250¬
{goto}TABLE2¬
/cC251..J251¬
C251..J490¬
{calc}
/rncTEST2¬¬
/xiTEST2=TEST¬/xcERASE¬                    | this is a loop which finds the maximum
/xiTEST2=TEST¬/xgTIME¬                     | load applied.   once found the loop
/rndTEST2¬                                 | invokes a subroutine that erases the
{down}                                     | data ten points beyond the maximum.
/rncTEST2¬¬                                | see the "ERASE" sub macro.
/xgLOOP¬                                   | after erasing control is passed to the
                                           | "TIME" macro


FAILURE

{calc}                           | this sub macro finds and copies the failure
/dqriINPUT¬                      | point to another location on the spreadsheet.
cCRITERION¬
oOUTPUT¬
eq
/xgPRINT¬


ERASE

{DOWN}          | this is the macro which erases all extraneous data from
{DOWN}          | the spreadsheet.   the cell pointer moves down ten lines
{DOWN}          | beyond the failure point and then proceeds to erase.
{DOWN}          | once finished control reverts back to the calling macro
{DOWN}
{DOWN}
{DOWN}
{DOWN}
{DOWN}
{DOWN}
{DOWN}
{DOWN}
{left}
{left}
/re
.{right}
{right}
{right}
{right}
{right}
{right}
{right}
{right}
{right}
{end}
{down}¬
/xr
```

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TIME MACRO

```
/xiTM>99999¬/xgTIME2¬          | this macro converts the time from a
{goto}TM¬                      | string of numbers into a readable form
{edit}{home}'                  | eg:123456 becomes 12:34:56
{right}:                       | this macro works on numbers smaller
{right}                        | than 99999
{right}:¬
{down}
/rncTEST3¬¬
/xiTEST3=0¬/xgFAIL¬
/rndTEST3¬
/xgLOOP2¬
{left}
```

TIME2 MACRO

```
{goto}TM¬
{edit}{home}'                  | this macro converts number strings into
{right}                        | readable times.  this macro works on
{right}:                       | times less than 9:59:59
{right}
{right}:¬
{down}
/rncTEST3¬¬
/xiTEST3=0¬/xgFAIL¬
/rndTEST3¬
/xgLOOP3¬
```

PRINT MACRO

```
/cIDA¬IDAA¬                  | this macro creates the print files into
/pfUSR\GARYV\TENSILE\PRW         | which go the SI table of data as well as
H12                          | SUMMARY of data.
¬
rA1..H244¬
gcrq
{goto}A245¬
/cIDA¬IDAB¬
/pfPSI
H12
¬
r.
{end}{down}
{end}{down}
{right}
{right}
{right}
{right}
{right}
{right}
{right}
{right}
{right}¬
gcrq
/cIDA¬IDAC¬
/cIDA¬IDAD¬
/pfUSR\GARYV\TENSILE\PSUM
H12
¬
rSUMMARY¬
gcrq
/xr
```

D.10.3 Instructions for Using the Macro Program for Data Processing

INSTRUCTIONS FOR USING LOTUS 1-2-3 SPREADSHEETS

FOR TENSILE SPLITTING DATA CALCULATIONS

The computer is setup in such a way that LOTUS 1-2-3 can be called up from any directory in the computer. When you have turned the computer on and you are at the "C:\>' prompt type in the following command "123" and LOTUS will be loaded into the computer.

From there type in "/fr" (/ file retrieve) and a series of directory names will appear on the command line. Choose the directory named "USR" then another series of directories will appear, this time choose the one named "GARYV" and finally one more list of directories will appear, choose the one named "TENSILE". Then a file name called "TSPLIT" will appear and press the return key. The screen will blank out for a few seconds and then the worksheet will appear on screen.

On the command line a menu will appear with the following choices:

Enter Data   Process   Quit

Point to the operation you wish to perform and press the enter key or else press the first letter of the command (i.e. E, P, Q).

ENTER DATA

If you choose to enter or edit data the computer will move the cell pointer to the first line of data. In this case data refers to the "FILENAME", the "TEST TEMP." and the "THICKNESS". This data must be entered in order for the computer to know which files you wish to process. The files that are to be processed must have been copied into directory "\USR\GARYV \TENSILE" previous to starting the processing.

The data must be entered under the correct headings as follows:

FILENAME   TEST TEMP   THICKNESS

The filename does not require the ".PRN" at the end, the computer assumes this file designation. The test temp can be any number positive or negative. The thickness must be input in INCH !!!! The data must be entered in columnar form so to move from cell location to cell location use the cursor keys.

Once you have finished entering or editing the data press the "Alt" and "A" keys simultaneously to return to the command menu.

PROCESS

If you wish to process the data then use this command and the computer will automatically begin processing the data. The computer requires approximately 20 minutes to complete the calculations for each set of test data. Once the calculations are completed for a set of data the computer will write the results onto the hard disk for later retrieval. The computer will then erase the calculated data and begin calculations on the next data set. When the computer has finished processing all of the data sets the command menu will reappear on the screen.

QUIT

This command causes the computer to save the worksheet and exit from LOTUS 1-2-3.

Once you have exited from LOTUS you can print out any of the processed data by going to the directory named "C: USR GARYV TENSILE >" and typing in the following command:

```
PRINT FILENAME.PRN
```

D.10.4 Sample Printout of Processed Test Data

```
                                                                                STRAIN
  TIME      READING    LOAD      LVDT       LVDT                 VERTICAL  STRESS   RATE   STIFFNESS
(HHMMSS)    NUMBER     (KG)         A          B        A+B        LVDT    (kPa) (mm/min)     [MPa]
 9:34:52         1       .0        .0         .0         .0          .0       .0       .0        .0
 9:34:53         2       .0   0.00005     .00000     .00000     0.03831       .0    2.299     105.0
 9:34:54         3       .0   0.00002     .00000    0.00004     0.01815       .0   -1.149        .0
 9:34:55         4       .0    .00000     .00000     .00000     0.09620       .0    4.022     105.0
 9:34:56         5       .0   0.00005     .00000     .00000     0.59379       .0   30.456     105.0
 9:34:57         6     26.8   0.00002    0.00002    0.00004     0.63210     24.1    2.299    1155.1
 9:34:58         7     56.1   0.00003    0.00006    0.00004     0.59814     50.4    4.022    2415.2
 9:34:59         8     87.6   0.00007    0.00007    0.00008     0.62253     78.9   -4.597    1880.2
 9:35:00         9    117.1   0.00007    0.00010    0.00004     0.68957    105.1    4.022    5040.5
 9:35:01        10    143.8   0.00010    0.00010    0.00008     0.60337    129.2   -5.172    3087.8
 9:35:02        11    170.7   0.00010    0.00012    0.00008     0.61295    153.3    0.575    3675.3
 9:35:03        12    195.1   0.00012    0.00012    0.00011     0.28816    175.3  -20.687    2800.3
 9:35:04        13    222.0   0.00012    0.00017    0.00011     0.29680    199.3    1.724    3185.3
 9:35:05        14    248.8   0.00015    0.00017    0.00015     0.27774    223.4   -1.149    2677.7
 9:35:06        15    278.0   0.00017    0.00022    0.00019     0.27774    249.7    0.000    2394.2
 9:35:07        16    304.9   0.00017    0.00024    0.00018     0.28816    273.8   -0.575    2625.2
 9:35:08        17    326.8   0.00022    0.00029    0.00022     0.27774    293.5    0.575    2345.2
 9:35:09        18    353.7   0.00022    0.00029    0.00027     0.28816    317.6   -0.575    2175.2
 9:35:10        19    378.0   0.00022    0.00034    0.00027     0.29680    339.5    1.724    2325.2
 9:35:11        20    404.8   0.00027    0.00037    0.00030     0.27774    363.6   -1.149    2178.9
 9:35:12        21    428.3   0.00027    0.00041    0.00030     0.30647    385.5    1.724    2310.2
 9:35:13        22    453.7   0.00032    0.00041    0.00034     0.28816    407.4   -2.299    2170.2
 9:35:14        23    480.5   0.00034    0.00046    0.00039     0.28816    431.5    0.000    2068.7
 9:35:15        24    502.4   0.00037    0.00049    0.00046     0.27774    451.2    0.575    1802.7
 9:35:16        25    526.8   0.00039    0.00054    0.00046     0.30647    473.1    1.724    1890.2
 9:35:17        26    551.2   0.00044    0.00059    0.00049     0.28732    495.1   -1.149    1829.6
 9:35:18        27    573.2   0.00049    0.00059    0.00053     0.32563    514.8    2.299    1762.7
 9:35:19        28    597.6   0.00049    0.00066    0.00057     0.31605    536.7   -0.575    1715.2
 9:35:20        29    619.5   0.00054    0.00068    0.00061     0.34478    556.4    1.724    1667.0
 9:35:21        30    643.9   0.00056    0.00073    0.00065     0.30647    578.3   -2.299    1630.7
 9:35:22        31    665.9   0.00061    0.00076    0.00068     0.27774    598.0   -1.724    1592.6
 9:35:23        32    687.8   0.00063    0.00083    0.00072     0.32563    617.7    2.873    1558.6
 9:35:24        33    712.2   0.00066    0.00088    0.00076     0.28732    639.6   -2.299    1533.1
 9:35:25        34    734.1   0.00071    0.00093    0.00080     0.32563    659.3    2.299    1505.1
 9:35:26        35    756.5   0.00076    0.00102    0.00088     0.31605    681.2   -0.575    1419.8
 9:35:27        36    778.0   0.00080    0.00105    0.00091     0.34478    698.8    1.724    1395.8
 9:35:28        37    800.0   0.00083    0.00112    0.00095     0.34478    718.5    0.000    1377.7
 9:35:29        38    819.5   0.00088    0.00115    0.00099     0.33521    736.0   -0.575    1357.0
 9:35:30        39    841.5   0.00093    0.00120    0.00103     0.31605    755.7   -1.149    1341.8
 9:35:31        40    863.4   0.00098    0.00124    0.00110     0.34478    775.4    1.724    1281.8
 9:35:32        41    882.9   0.00102    0.00134    0.00118     0.34478    793.0    0.000    1226.2
 9:35:33        42    904.9   0.00107    0.00144    0.00122     0.33521    812.7   -0.575    1217.5
 9:35:34        43    926.8   0.00112    0.00146    0.00129     0.34478    832.4    0.575    1173.6
 9:35:35        44    946.3   0.00117    0.00154    0.00137     0.36394    849.9    1.149    1131.8
 9:35:36        45    968.3   0.00124    0.00163    0.00145     0.36394    869.6    0.000    1097.1
 9:35:37        46    987.8   0.00129    0.00168    0.00148     0.36394    887.2    0.000    1090.5
 9:35:38        47   1007.3   0.00137    0.00176    0.00156     0.40225    904.7    2.299    1057.8
 9:35:39        48   1024.4   0.00144    0.00185    0.00164     0.37352    920.0   -1.724    1025.7
 9:35:40        49   1041.5   0.00146    0.00193    0.00171     0.37352    935.3    0.000     996.4
 9:35:41        50   1063.4   0.00154    0.00200    0.00178     0.40225    955.1    1.724     974.1
 9:35:42        51   1078.0   0.00161    0.00212    0.00186     0.39267    968.2   -0.575     947.2
 9:35:43        52   1095.1   0.00168    0.00220    0.00194     0.41182    983.5    1.149     924.5
 9:35:44        53   1112.2   0.00176    0.00227    0.00202     0.38309    998.8   -1.724     903.5
 9:35:45        54   1126.8   0.00183    0.00239    0.00213     0.41182   1012.0    1.724     866.3
 9:35:45        55   1143.9   0.00193    0.00246    0.00221     0.43098   1027.3    1.149     849.1
 9:35:46        56   1161.0   0.00202    0.00256    0.00228     0.42140   1042.7   -0.575     833.1
 9:35:47        57   1178.0   0.00207    0.00266    0.00240     0.43098   1058.0    0.575     805.1
 9:35:48        58   1192.7   0.00217    0.00280    0.00247     0.42140   1071.2   -0.575     790.0
 9:35:49        59   1207.3   0.00229    0.00293    0.00258     0.42140   1084.3    0.000     764.4
 9:35:50        60   1222.0   0.00237    0.00302    0.00266     0.44056   1097.4    1.149     751.6
 9:35:51        61   1236.6   0.00246    0.00315    0.00282     0.42140   1110.6   -1.149     719.5
 9:35:52        62   1251.2   0.00256    0.00329    0.00289     0.44056   1123.7    1.149     706.8
 9:35:53        63   1261.0   0.00265    0.00339    0.00304     0.44056   1132.5    0.000     678.6
 9:35:54        64   1276.0   0.00276    0.00351    0.00312     0.43098   1147.8   -0.575     671.0
 9:35:55        65   1290.2   0.00280    0.00363    0.00327     0.45013   1158.8    1.149     645.8
 9:35:56        66   1302.4   0.00302    0.00378    0.00342     0.46929   1169.7    1.149     623.1
 9:35:57        67   1314.6   0.00312    0.00395    0.00354     0.45013   1180.7   -1.149     608.6
 9:35:58        68   1324.4   0.00324    0.00410    0.00369     0.45013   1189.4    0.000     587.8
 9:35:59        69   1336.6   0.00339    0.00424    0.00384     0.45871   1200.4    0.575     569.8
 9:36:00        70   1346.3   0.00349    0.00439    0.00400     0.46929   1209.2    0.575     552.1
 9:36:01        71   1356.1   0.00363    0.00461    0.00415     0.48844   1217.9    1.149     535.6
 9:36:02        72   1365.9   0.00378    0.00476    0.00430     0.48844   1226.7    0.000     520.4
 9:36:03        73   1375.6   0.00393    0.00490    0.00445     0.46929   1235.4   -1.149     506.2
 9:36:04        74   1382.9   0.00410    0.00512    0.00460     0.48844   1242.[illegible]    1.149     492.1
 9:36:05        75   1390.2   0.00424    0.00532    0.00478     0.47887   1248.6   -0.575     475.0
 9:36:06        76   1402.4   0.00441    0.00546    0.00498     0.48844   1259.5    0.575     460.9
 9:36:07        77   1407.3   0.00454    0.00566    0.00514     0.50760   1263.9    1.149     446.8
 9:36:08        78   1414.6   0.00476    0.00580    0.00536     0.49802   1270.5   -0.575     432.0
 9:36:09        79   1422.0   0.00493    0.00607    0.00552     0.51718   1277.1    1.149     422.2
 9:36:10        80   1431.7   0.00510    0.00637    0.00575     0.49802   1285.8   -1.149     408.2
 9:36:11        81   1436.6   0.00527    0.00656    0.00597     0.50760   1290.2    0.575     394.0
 9:36:12        82   1441.5   0.00546    0.00680    0.00616     0.51718   1294.6    0.575     383.1
 9:36:13        83   1446.3   0.00568    0.00707    0.00639     0.50760   1299.0   -0.575     370.7
 9:36:14        84   1451.2   0.00585    0.00732    0.00662     0.51718   1303.4    0.575     359.1
 9:36:15        85   1456.1   0.00600    0.00759    0.00685     0.51718   1307.7    0.000     348.3
 9:36:16        86   1461.0   0.00620    0.00790    0.00708     0.54591   1312.1    1.724     338.2
 9:36:17        87   1465.9   0.00634    0.00820    0.00731     0.54591   1316.5    0.000     328.7
 9:36:18        88   1470.7   0.00651    0.00846    0.00753     0.55548   1320.9    0.575     319.8
 9:36:19        89   1475.6   0.00668    0.00880    0.00775     0.55548   1325.3    0.000     311.4
 9:36:20        90   1480.5   0.00685    0.00917    0.00803     0.53633   1329.6   -1.149     302.1
 9:36:21        91   1485.4   0.00702    0.00946    0.00828     0.54591   1334.0    0.575     293.4
 9:36:22        92   1487.8   0.00720    0.00988    0.00856     0.55548   1336.2    0.575     284.7
 9:36:23        93   1487.8   0.00739    0.01027    0.00887     0.17239   1336.2  -22.986     274.9
 9:36:24        94   1490.2   0.00761    0.01068    0.00917     0.17239   1338.4    0.000     266.2
 9:36:25        95   1490.2   0.00778    0.01110    0.00951     0.16281   1338.4   -0.575     256.6
 9:36:26        96   1492.7   0.00800    0.01154    0.00985     0.19155   1340.6    1.724     248.1
 9:36:27        97   1490.2   0.00822    0.01202    0.01020     0.18197   1338.4   -0.575     239.4
 9:36:28        98   1487.8   0.00846    0.01256    0.01054     0.17239   1336.2   -0.575     231.2
 9:36:29        99   1485.4   0.00866    0.01315    0.01096     0.20112   1334.0    1.724     222.1
 9:36:30       100   1482.9   0.00890    0.01371    0.01136     0.22986   1331.8    1.724     213.5
 9:36:31       101   1482.9   0.00915    0.01434    0.01180     0.22986   1331.8    0.000     206.0
 9:36:32       102   1480.5   0.00936    0.01485    0.01229     0.24901   1329.6    1.149     197.3
 9:36:33       103   1478.0   0.00966    0.01539    0.01271     0.24901   1327.4    0.000     190.5
```

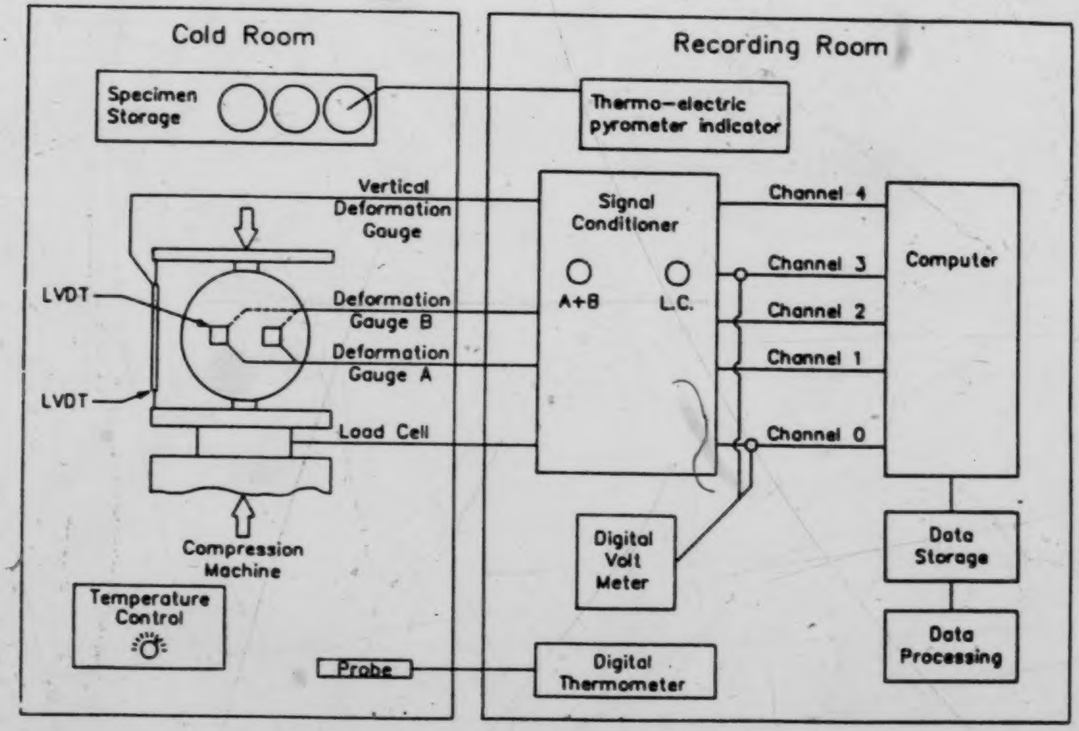
Cold Room
Specimen Storage
Vertical Deformation Gauge
LVDT
LVDT
Deformation Gauge B
Deformation Gauge A
Load Cell
Compression Machine
Temperature Control
Probe
Recording Room
Thermo-electric pyrometer indicator
Signal Conditioner
A+B
L.C.
Channel 4
Channel 3
Channel 2
Channel 1
Channel 0
Computer
Digital Volt Meter
Data Storage
Data Processing
Digital Thermometer

Figure D1 Schematic of Test Equipment Layout

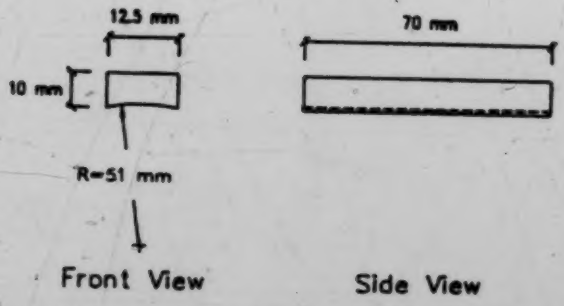
12.5 mm
10 mm
R=51 mm
70 mm
Front View
Side View

Figure D2 Load Bearing Strips

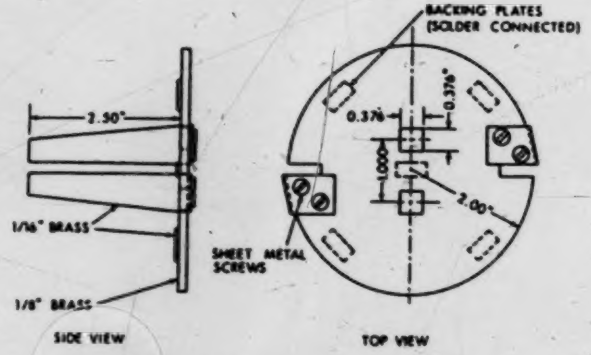
BACKING PLATES
(SOLDER CONNECTED)
2.50"
0.376
0.376"
1.000
2.00"
1/16" BRASS
1/8" BRASS
SHEET METAL
SCREWS
SIDE VIEW
TOP VIEW

Figure D3 **Gauge Point Jig**

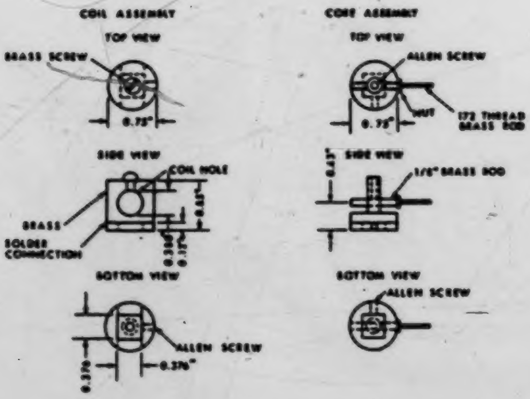
COIL ASSEMBLY
TOP VIEW
BRASS SCREW
0.75"
SIDE VIEW
COIL HOLE
BRASS
SOLDER
CONNECTION
BOTTOM VIEW
ALLEN SCREW
0.376"
0.376
CORE ASSEMBLY
TOP VIEW
ALLEN SCREW
NUT
172 THREAD
BRASS ROD
0.75"
SIDE VIEW
1/8" BRASS ROD
BOTTOM VIEW
ALLEN SCREW

Figure D4 **Displacement Gauge Core and Coil Assemblies**

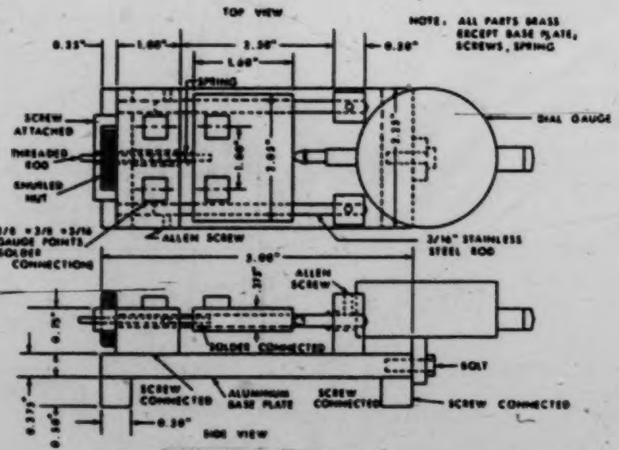
TOP VIEW
NOTE: ALL PARTS BRASS
EXCEPT BASE PLATE,
SCREWS, SPRING
0.33"
1.00"
2.30"
1.60"
0.20"
SPRING
SCREW
ATTACHED
THREADED
ROD
KNURLED
NUT
DIAL GAUGE
3/8 × 3/8 × 3/16
GAUGE POINTS
(SOLDER
CONNECTION)
ALLEN SCREW
3/16" STAINLESS
STEEL ROD
3.00"
ALLEN
SCREW
SOLDER CONNECTED
BOLT
SCREW
CONNECTED
ALUMINUM
BASE PLATE
SCREW
CONNECTED
SCREW CONNECTED
0.20"
SIDE VIEW

Figure D5 **Displacement Gauge Calibration Jig**

Appendix E

Tensile Splitting Test Results

GULF PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
RR19	0	0.00464	1641.4	645
RR12	0	0.00632	1748.4	504.9
RR4	0	0.00186	1051.8	1029
RR11	0	0.00483	1196.1	451.5
RR8	0	0.00575	1549.2	491.8
NO. OF TEST	=	5	5	5
MEAN	=	0.00468	1437.38	624.44
ST. DEVIATION	=	0.001536	267.4880	212.5478
COEF VARIATION		32.84070	18.60941	34.03815

GULF PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
RR14	-10	0.00156	1962.9	2295.1
RR16	-10	0.00118	2645	4090.2
RR6	-10	0.00061	1768.6	5299
NO. OF TEST	=	3	3	3
MEAN	=	0.001116	2125.5	3894.766
ST. DEVIATION	=	0.000390	375.8087	1234.098
COEF VARIATION		34.96234	17.68095	31.68607

GULF PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
RR17	-20	0.00061	2729.4	8177.6
RR15	-20	0.0003	2847.7	17064
RR9	-20	0.00034	1478.9	7877.4
RR13	-20	0.00049	1474.8	5438.5
NO. OF TEST	=	4	4	4
MEAN	=	0.000435	2132.7	9639.375
ST. DEVIATION	=	0.000123	657.1839	4416.269
COEF VARIATION		28.36543	30.81464	45.81489

GULF PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
RR18	-30	0.00046	2304.4	9205.8
RR1	-30	0.00042	2187.8	9534.7
RR3	-30	0.00046	2082.9	8320.9
RR10	-30	0.00023	1813.3	14487.7
RR2	-30	0.00053	2495.8	8546
NO. OF TEST	=	5	5	5
MEAN	=	0.00042	2176.84	10019.02
ST. DEVIATION	=	0.000101	227.6458	2276.769
COEF VARIATION		24.14055	10.45762	22.72447

GULF PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
RW16	0	0.0067	1082.1	294.7
RW9	0	0.00788	1019.9	236.2
RW6	0	0.01054	1172.9	203
RW1	0	0.0062	1015.3	298.6
RW11	0	0.01202	954.2	144.8
NO. OF TEST	=	5	5	5
MEAN	=	0.008668	1048.88	235.46
ST. DEVIATION	=	0.002250	74.04902	57.91281
COEF VARIATION		25.96409	7.059818	24.59560

GULF PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
RW15	-10	0.0019	1732	1660.6
RW21	-10	0.00217	2081.1	1750.3
RW22	-10	0.00167	1955.2	2130.2
RW12	-10	0.00027	2361	16169.2
RW19	-10	0.00224	2237.8	1818.2
NO. OF TEST	=	5	5	5
MEAN	=	0.00165	2073.42	4705.7
ST. DEVIATION	=	0.000719	219.2375	5733.929
COEF VARIATION		43.58414	10.57371	121.8507

GULF PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
RW3	-30	0.00042	3355.8	14624.6
RW13	-30	0.00038	2295.7	11005.2
RW7	-30	0.00046	2970.5	11866.7
RW2	-30	0.0008	3009.7	6870.4
RW5	-30	0.00046	2563.9	10242.3
NO. OF TEST	=	5	5	5
MEAN	=	0.000504	2839.12	10921.84
ST. DEVIATION	=	0.000150	369.9642	2509.425
COEF VARIATION		29.94914	13.03094	22.97621

GULF PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
RW25	-20	0.00133	3276.9	4488.2
RW20	-20	0.00164	2090.3	2330.4
RW17	-20	0.00114	2132.7	3408
RW23	-20	0.00202	3009.7	2722.3
RW14	-20	0.0016	3032.6	3461.4
NO. OF TEST	=	5	5	5
MEAN	=	0.001546	2708.44	3282.06
ST. DEVIATION	=	0.000299	496.4992	737.8055
COEF VARIATION		19.36001	18.33155	22.47995

H U S K Y PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
S4	-10	0.00171	2696.5	2872.6
S16	-10	0.00259	2126.1	1498.9
S13	-10	0.00103	2875.9	5106.1
S6	-10	0.00186	1830.1	1790.4
S12	-10	0.0038	2234.7	1071.3
NO. OF TEST	=	5	5	5
MEAN	=	0.002198	2352.66	2467.86
ST. DEVIATION	=	0.000941	382.1829	1447.227
COEF VARIATION		42.85646	16.24471	58.64302

H U S K Y PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
S11	0	0.00985	1340.6	248.1
S19	0	0.00704	1247.9	323.4
55	0	0.01488	1402	171.9
S7	0	0.00997	1178	215.5
S10	0	0.00932	1123.2	219.8
NO. OF TEST	=	5	5	5
MEAN	=	0.010212	1258.34	235.74
ST. DEVIATION	=	0.002562	102.2068	50.15243
COEF VARIATION		25.09495	8.122358	21.27446

H U S K Y PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
S18	-20	0.00099	2352.3	4337.2
S22	-20	0.00091	2975.1	5942.7
S14	-20	0.00072	2598.4	6555.9
S9	-20	0.00034	2290.3	12199.1
NO. OF TEST	=	4	4	4
MEAN	=	0.00074	2554.025	7258.725
ST. DEVIATION	=	0.000250	269.0339	2965.151
COEF VARIATION		33.90518	10.53372	40.84948

H U S K Y PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
S15	-30	0.00049	2160.9	7968.3
S21	-30	0.00088	2098.1	4373
S20	-30	0.00057	2853	9117.9
S17	-30	0.00053	2510	8594.8
NO. OF TEST	=	4	4	4
MEAN	=	0.000617	2405.5	7513.5
ST. DEVIATION	=	0.000154	302.2831	1858.284
COEF VARIATION		24.96699	12.56633	24.73261

H U S K Y PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
H14	0	0.01024	740.4	131.9
H3	0	0.0132	655.9	90.6
H7	0	0.01708	649.6	69.4
H19	0	0.01541	595	70.4
NO. OF TEST	=	4	4	4
MEAN	=	0.013982	660.225	90.575
ST. DEVIATION	=	0.002561	51.99501	25.31386
COEF VARIATION		18.32133	7.875348	27.94796

H U S K Y PEN200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
H5	-10	0.00365	805.8	402.4
H10	-10	0.00544	1413.9	474
H2	-10	0.00388	1256.8	590.7
H20	-10	0.00609	1162.5	348.3
H18	-10	0.00769	1427.5	338.8
NO. OF TEST	=	5	5	5
MEAN	=	0.00535	1213.3	430.84
ST. DEVIATION	=	0.001488	226.5617	93.28563
COEF VARIATION		27.82750	18.67318	21.65203

H U S K Y PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
H9	-20	0.00495	3011.9	1110.7
H16	-20	0.00658	3122.6	865.3
H13	-20	0.00213	2651.4	2269.7
H1	-20	0.00244	2472.7	1852.2
NO. OF TEST	=	4	4	4
MEAN	=	0.004025	2814.65	1524.475
ST. DEVIATION	=	0.001836	263.3064	563.1352
COEF VARIATION		45.62051	9.354855	36.93962

H U S K Y P E N 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
H17	-30	0.00042	2758.4	12021.4
H12	-30	0.00042	2489.3	10848.5
H11	-30	0.00042	3061.2	13340.8
NO. OF TEST	=	3	3	3
MEAN	=	0.00042	2769.633	12070.23
ST. DEVIATION	=	1.8E-12	233.6122	1018.062
COEF VARIATION		0.000000	8.434772	8.434492

IMPERIAL PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
CL7	0	0.0067	1522	414.5
CL22	0	0.0067	1549.8	422.1
CL3	0	0.00723	1289.8	325.4
CL19	0	0.00651	1168.7	327.6
NO. OF TEST =		4	4	4
MEAN =		0.006785	1382.575	372.4
ST. DEVIATION =		0.000268	159.4939	45.98516
COEF VARIATION		3.955412	11.53600	12.34832

IMPERIAL PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
CL16	-20	0.00046	2741.1	10950.2
CL9	-20	0.00084	2675.2	5829.4
CL2	-20	0.00057	2430.7	7768.4
NO. OF TEST =		3	3	3
MEAN =		0.000623	2615.666	8182.666
ST. DEVIATION =		0.000159	133.5295	2110.980
COEF VARIATION		25.61268	5.104990	25.79820

IMPERIAL PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
C8	0	0.01556	964.6	113.1
C19	0	0.01256	751.3	109.1
C3	0	0.00829	688.9	151.5
C22	0	0.01377	590.8	78.2
C21	0	0.01035	613.3	108.1
NO. OF TEST =		5	5	5
MEAN =		0.012106	721.78	112
ST. DEVIATION =		0.002551	134.0430	23.35602
COEF VARIATION		21.07624	18.57118	20.85359

IMPERIAL PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
C7	-20	0.00278	2152.4	1413.5
C23	-20	0.00175	2037	2122.8
C10	-20	0.00152	2344.6	2809.9
C16	-20	0.00274	2744.4	1827.2
C4	-20	0.00167	2839.2	3093.4
NO. OF TEST =		5	5	5
MEAN =		0.002092	2423.52	2253.36
ST. DEVIATION =		0.000550	317.7690	619.5848
COEF VARIATION		26.31651	13.11188	27.49604

IMPERIAL PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
CL21	-10	0.0019	2397.7	2298.9
CL17	-10	0.00236	2014.4	1557.5
CL12	-10	0.00251	2125.5	1543.8
NO. OF TEST =		3	3	3
MEAN =		0.002256	2179.2	1800.066
ST. DEVIATION =		0.000259	161.0227	352.7727
COEF VARIATION		11.50056	7.389076	19.59776

IMPERIAL PEN 85/100

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
CL13	-30	0.00049	2764.9	10195.9
CL4	-30	0.00046	2573.6	10281.1
CL1	-30	0.00099	2224.8	4102.1
CL5	-30	0.00061	3320.7	9949.3
CL11	-30	0.00042	2667.2	11624
NO. OF TEST =		5	5	5
MEAN =		0.000594	2710.24	9230.48
ST. DEVIATION =		0.000207	355.4782	2629.895
COEF VARIATION		35.00064	13.11611	28.49143

IMPERIAL PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
C6	-10	0.00468	2105.9	820.8
C1	-10	0.00198	1520.1	1401.4
C17	-10	0.00186	1359.7	1330.3
C2	-10	0.00396	1662.6	766.4
C11	-10	0.00152	1550.5	1858.2
NO. OF TEST =		5	5	5
MEAN =		0.0028	1639.76	1235.42
ST. DEVIATION =		0.001270	252.3995	404.0534
COEF VARIATION		45.38497	15.39246	32.70575

IMPERIAL PEN 200/300

SAMPLE NUMBER	SPECIMEN TEMP (C)	STRAIN (mm/mm)	STRESS (kPa)	STIFFNESS (MPa)
C9	-30	0.00068	2801	7459.7
C15	-30	0.00068	3772.8	10047.9
C5	-30	0.00049	3435.2	12667.7
C20	-30	0.00034	2073.1	11042.3
C14	-30	0.00072	2983.8	7528.3
NO. OF TEST =		5	5	5
MEAN =		0.000582	3013.18	9749.18
ST. DEVIATION =		0.000145	580.4752	2022.532
COEF VARIATION		24.93244	19.26453	20.74566